Physical Conditions of the Nearby Gas

Edward B. Jenkins
Princeton University Observatory

What Kind of Gaseous Material are we Considering?

- Warm clouds ($T \sim 7000$ K) with $n_{\mathbf{H}} \sim 0.2$ cm^{-3} that is partially ionized, with a surprisingly high fractional ionization of He, indicating the presence of a radiation field that has energetic photons
- These clouds are similar to the material that is in the immediate vicinity of the Sun (just outside the heliosphere)

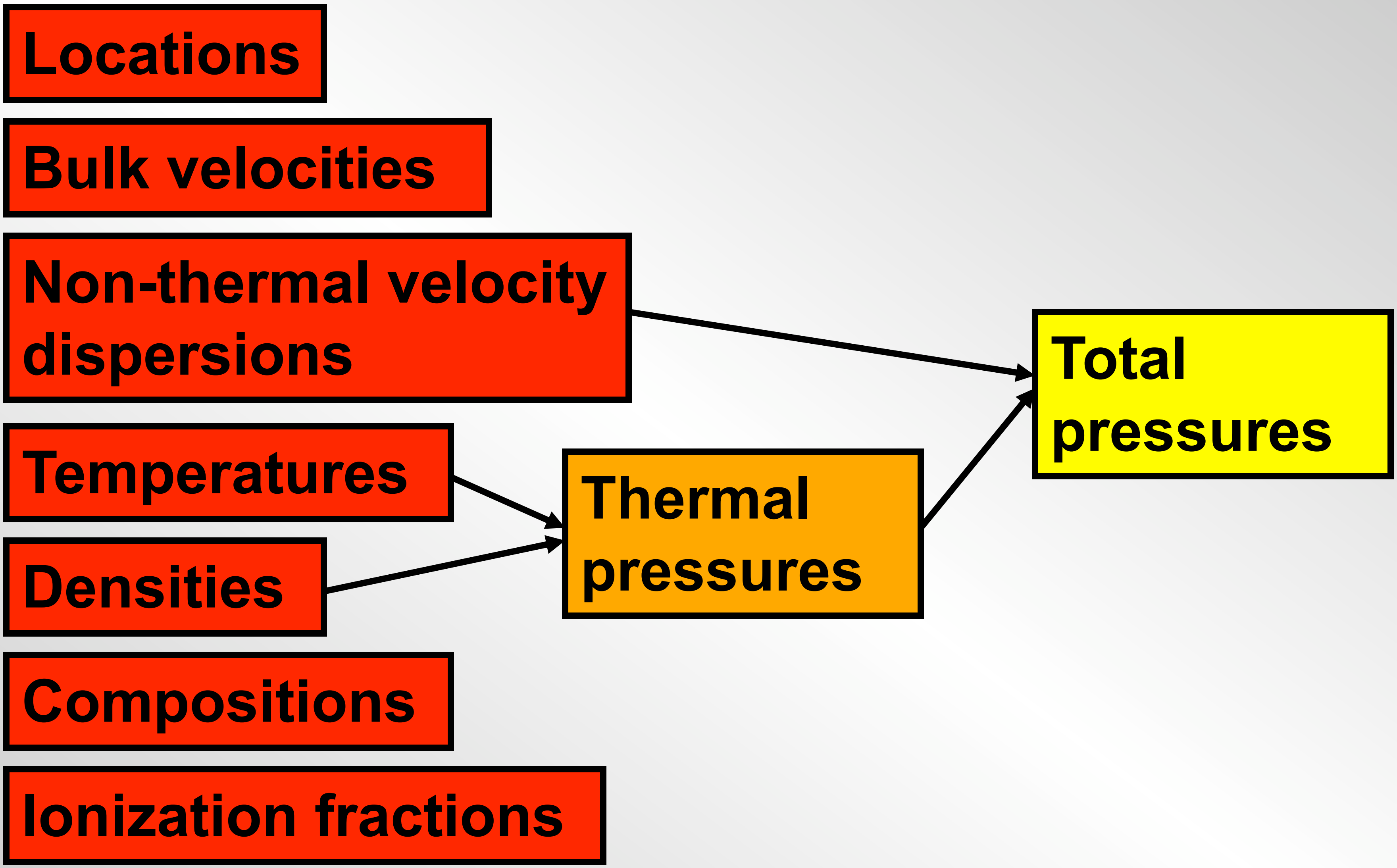
What Kind of Gaseous Material are we Considering?

- The clouds are confined by the pressure of an external medium, presumably gas with $T \sim 10^6$ K

Fundamental Issues

Locations	Geometrical arrangement in the sky, distances → distributions in 3D space
Bulk velocities	Collisions between clouds, leading to interaction zones and ρv^2 dynamical pressures?
Non-thermal velocity dispersions	Turbulence, MHD processes
Temperatures	Thermal equilibrium (& its time scale)
Densities	
Compositions	Apportionment of elements in gas phase vs. dust
Ionization fractions	Density of ionizing radiation, history of the gas (ionization/recombination time scale)

Fundamental Issues



Fundamental Issues

Locations

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Bulk velocities

Collisions between clouds, leading to interaction zones and ρv^2 dynamical pressures?

Non-thermal velocity dispersions

Turbulence, MHD processes

Temperatures

Thermal equilibrium (& its time scale)

Densities

Compositions

Apportionment of elements in gas phase vs. dust

Ionization fractions

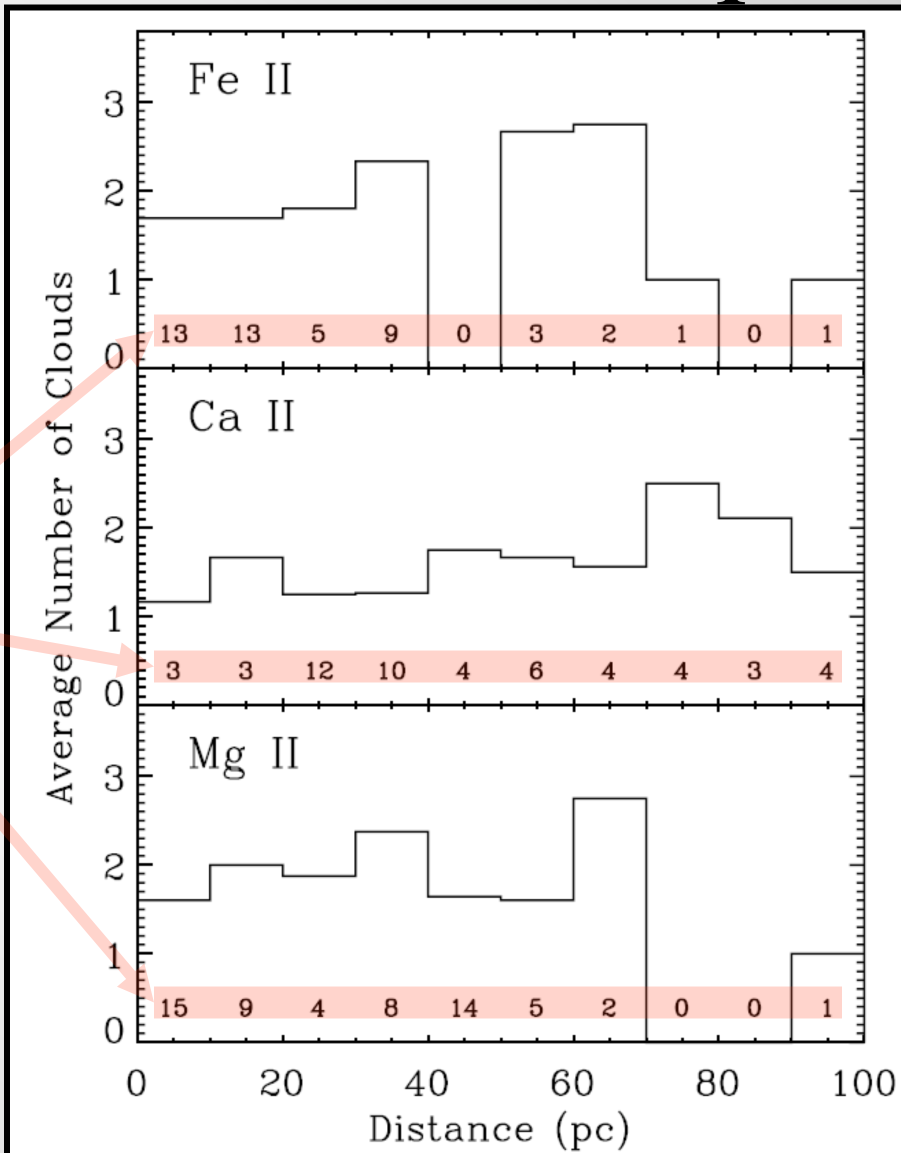
Density of ionizing radiation, history of the gas (ionization/recombination time scale)

Most Clouds are Within ~ 15 pc

- Number of identifiable velocity components as a function of distance

Number of sightlines used in each bin

Redfield & Linsky, 2004, ApJ, 602, 776

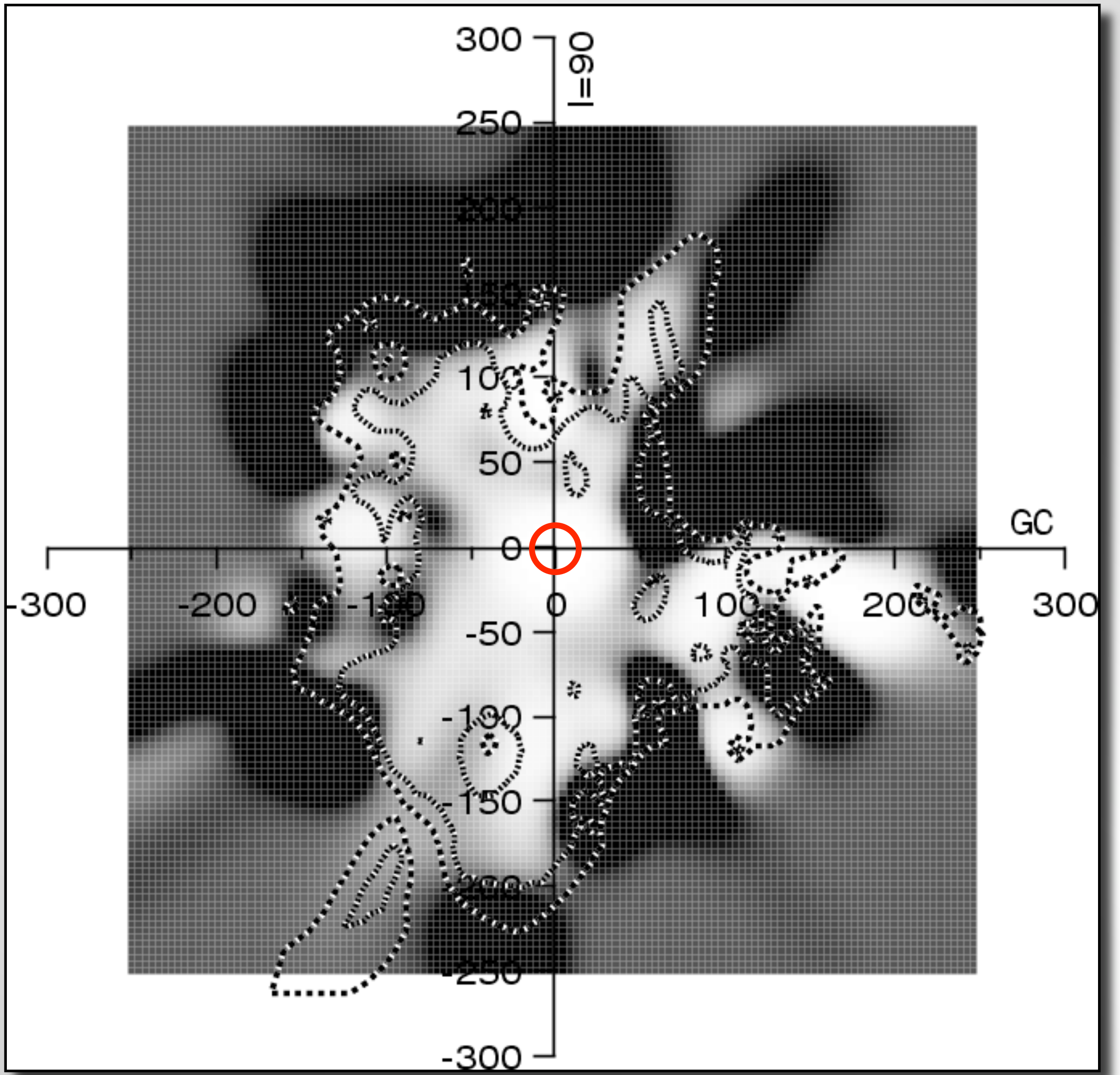


Most Clouds are Within ~ 15 pc

- This is supported by the observations of astrospheres around nearby stars, seen as Lα absorption at a displaced velocity.
- They are seen toward 59% of the stars in the sample that have $d < 10$ pc, but a much smaller fraction is seen for stars with $d > 10$ pc.
- This conclusion might be compromised by the fact that astrospheres are harder to detect as the foreground Lα from interstellar H starts to mask the astrospheric component.

Wood et al. ApJS, 159, 118

Layout Within the Local Bubble



Lallement et al. (2003), A&A, 411, 447

Local Clouds

Redfield & Linsky, 2008, ApJ, 673, 283

Measure absorption features toward nearby stars and interpret them as arising from contiguous clumps of gaseous matter, all of which have a kinematic behavior resembling a rigid body

The latest and most comprehensive survey, building on earlier work by various investigators, such as Crutcher, Lallement et al. & Frisch et al.

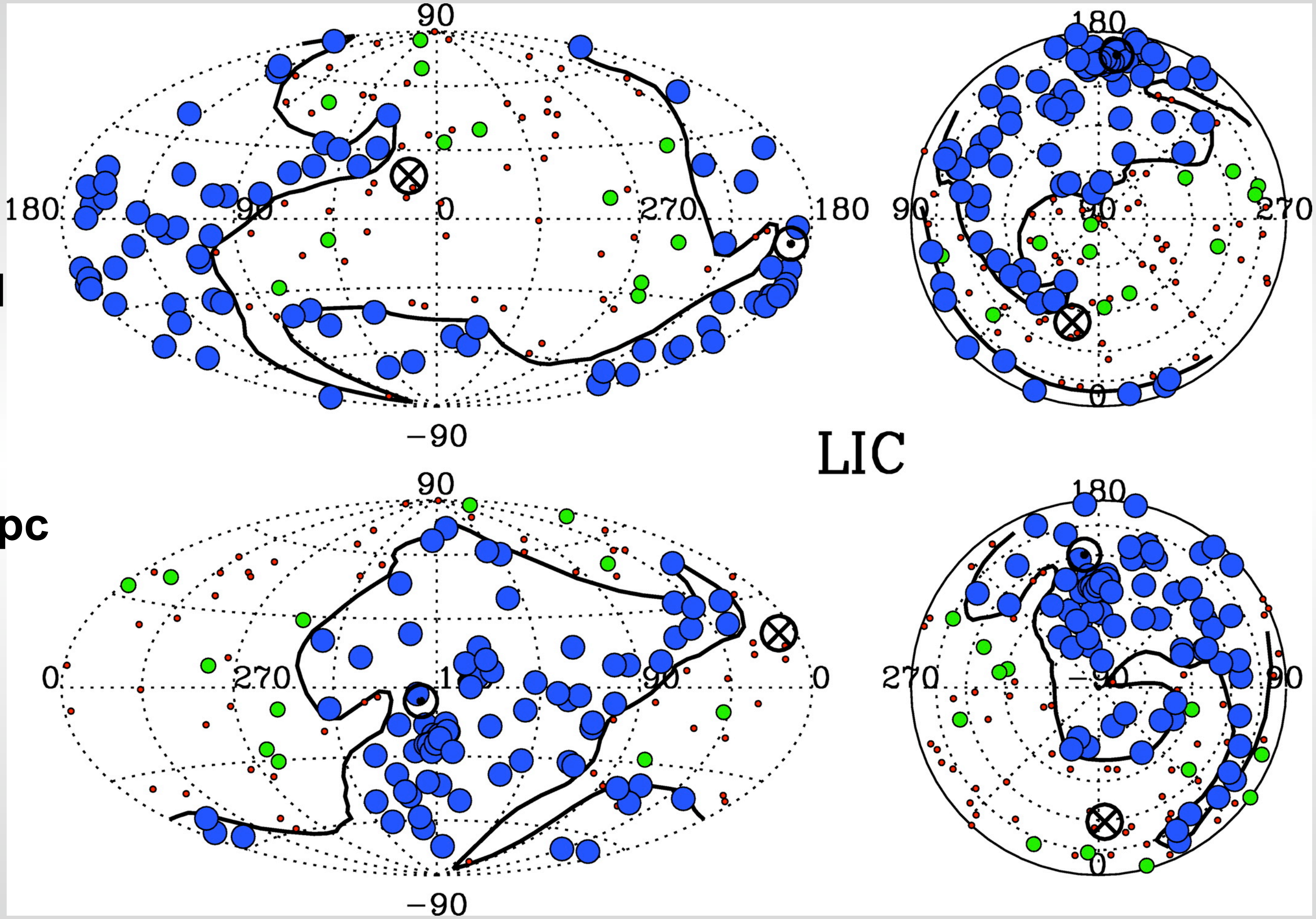
Local Clouds

Redfield & Linsky, 2008, ApJ, 673, 283

⊗ **Upwind direction**

⊙ **Downwind direction**

Closest star: 2.6 pc



● **Velocity comp. ident. with cloud and used to calculate *v***

● **Consistent velocity but ident. with another cloud**

● **Entirely wrong velocity**

Local Clouds

Redfield & Linsky, 2008, ApJ, 673, 283

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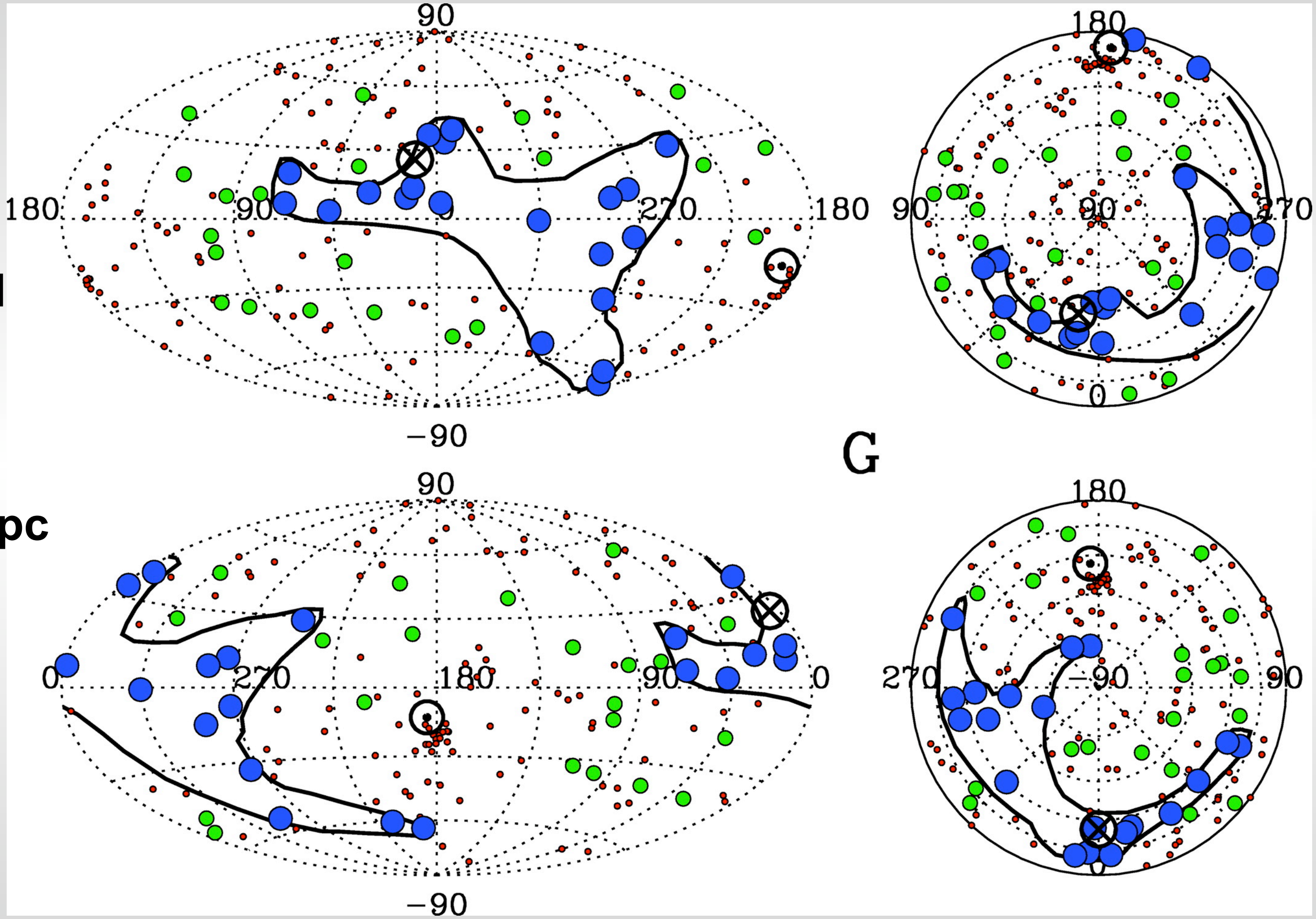
Closest star: 1.3 pc



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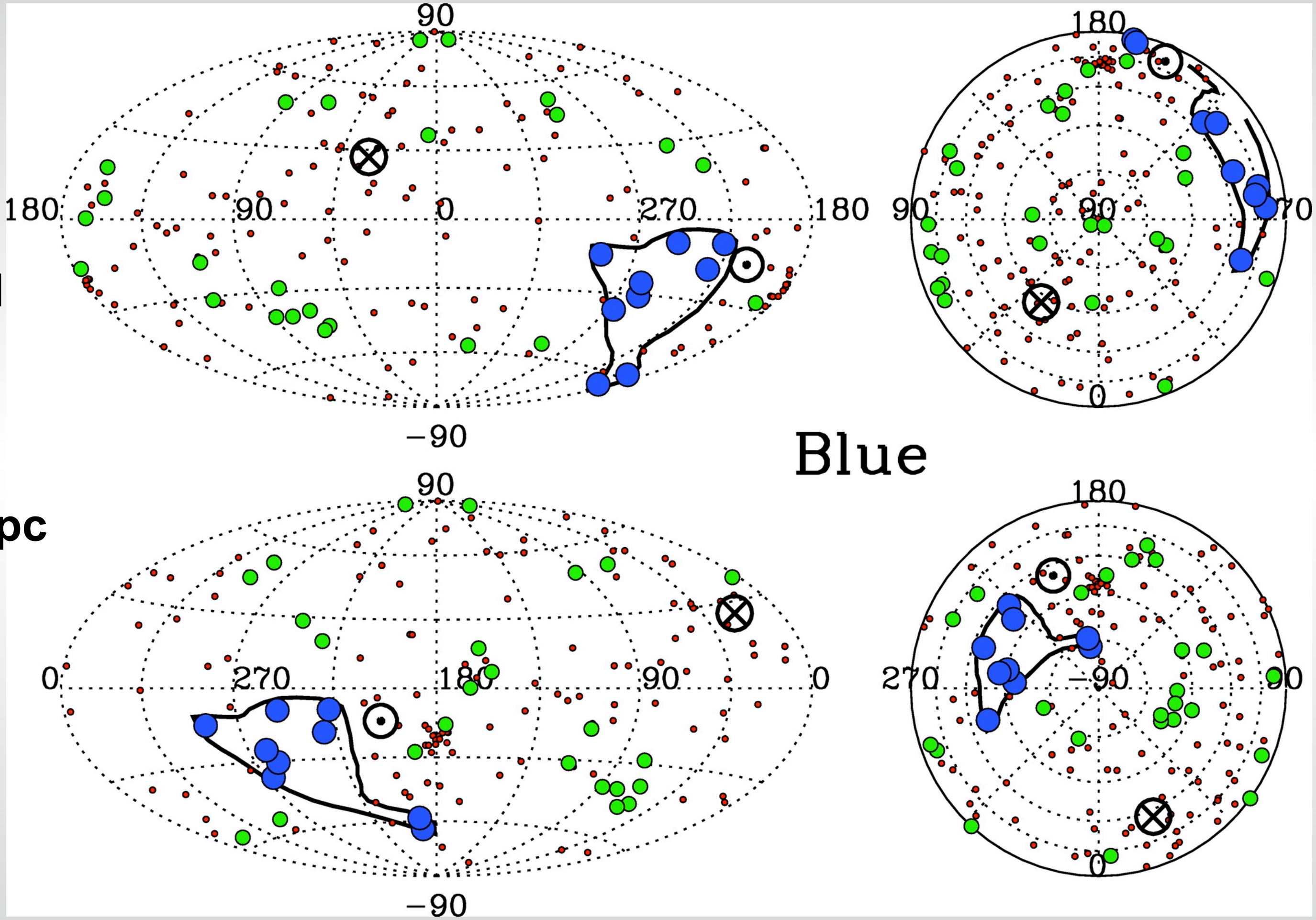

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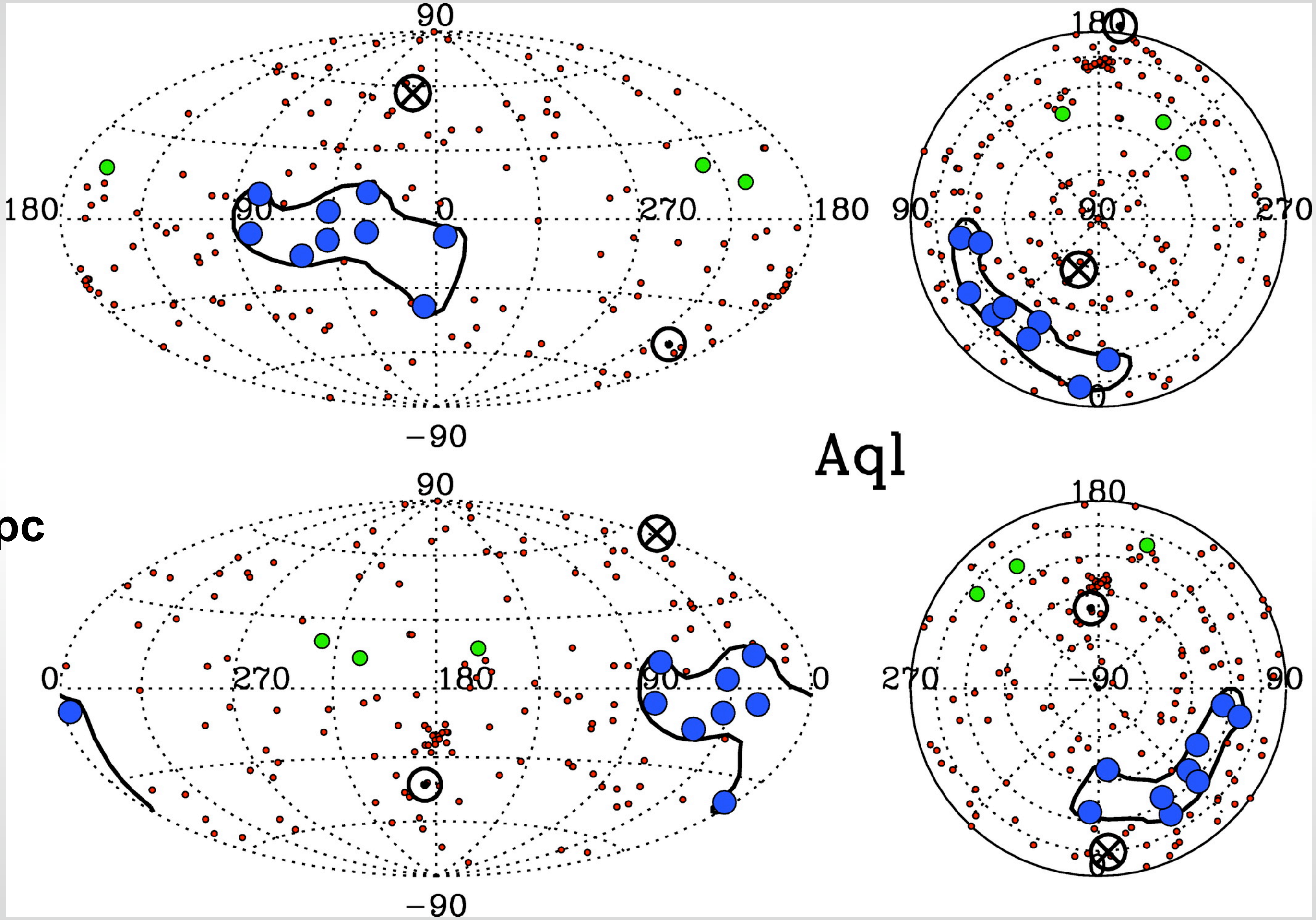
Closest star: 3.5 pc



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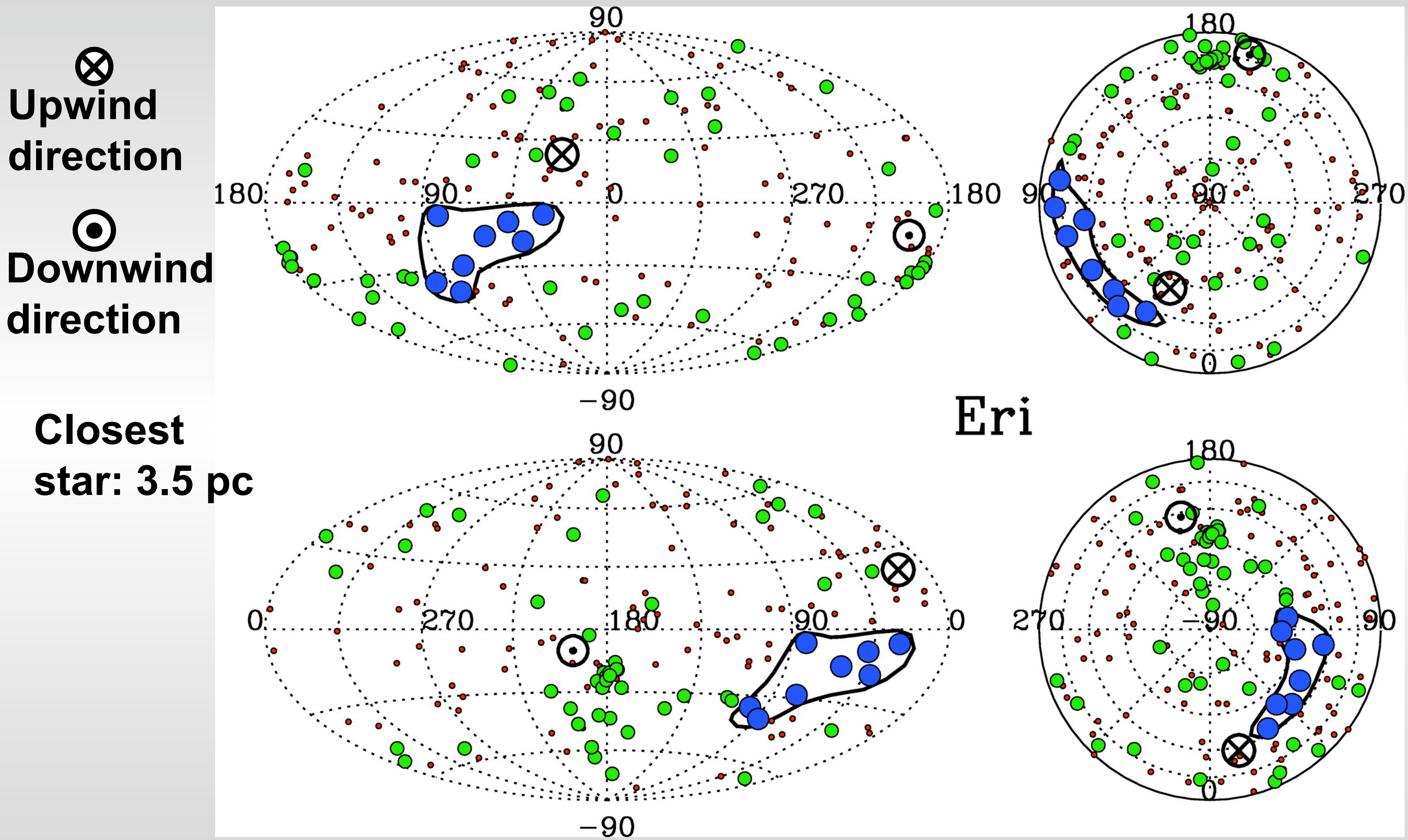

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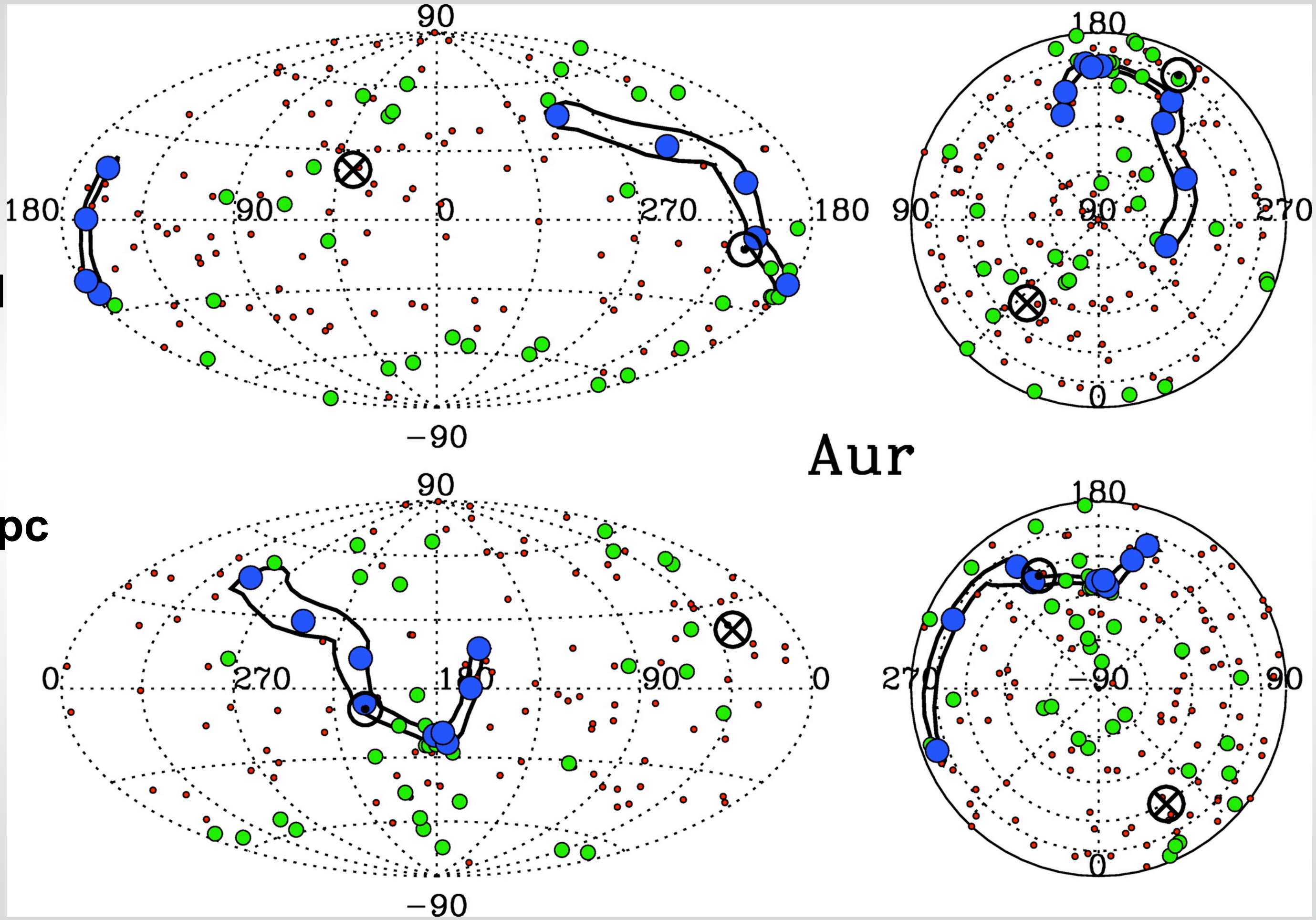

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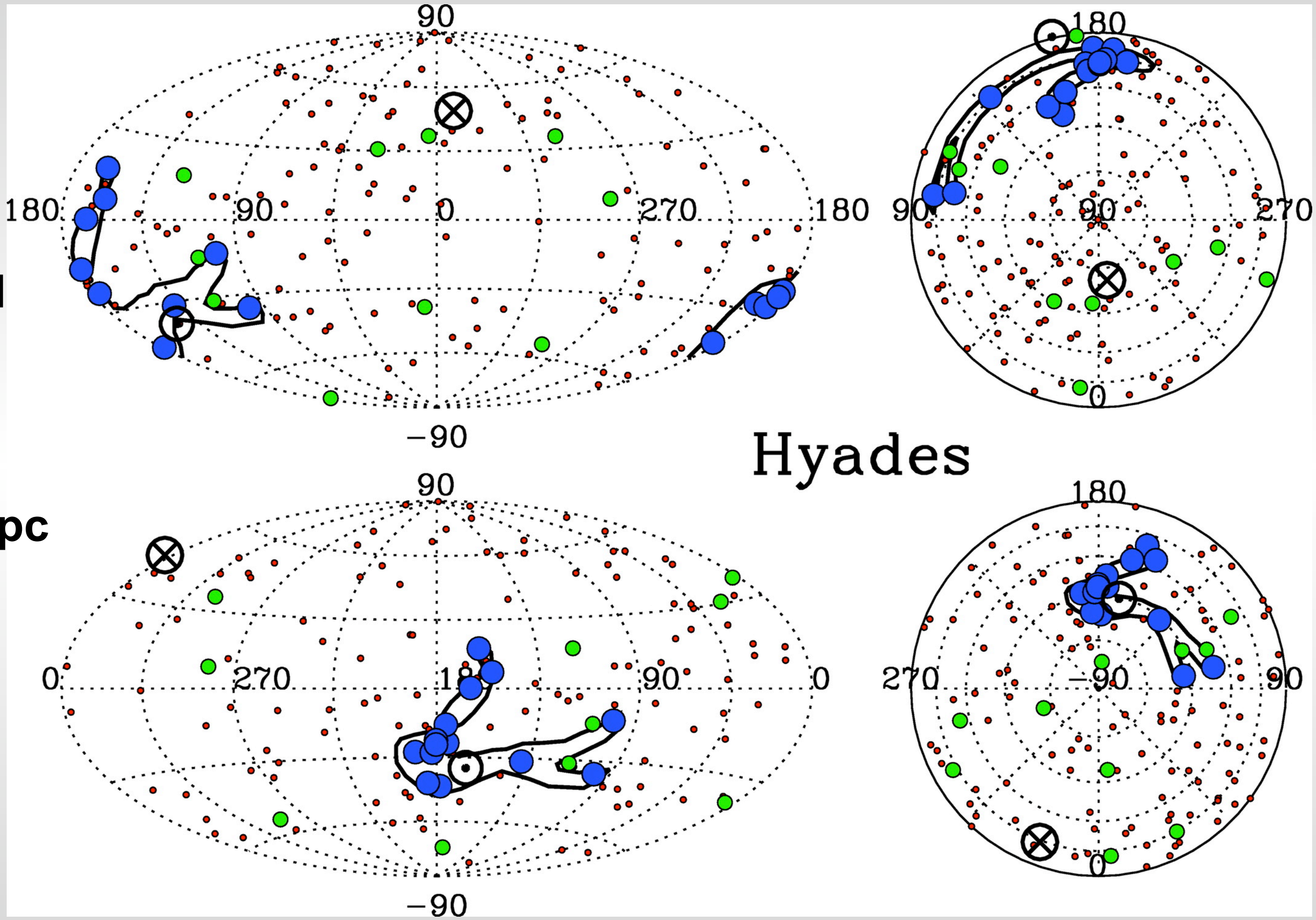
Closest star: 5.0 pc



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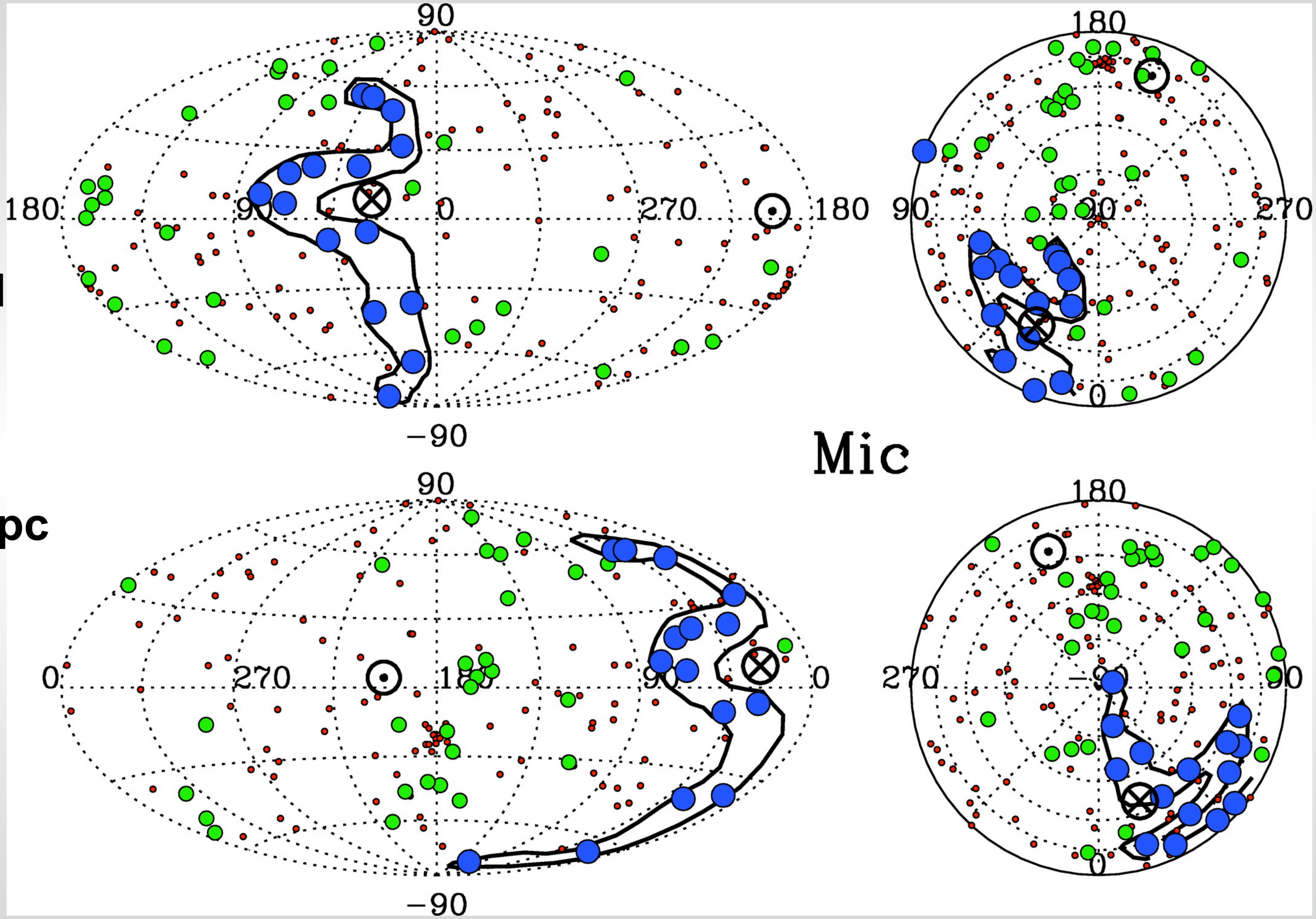
Closest star: 5.1 pc



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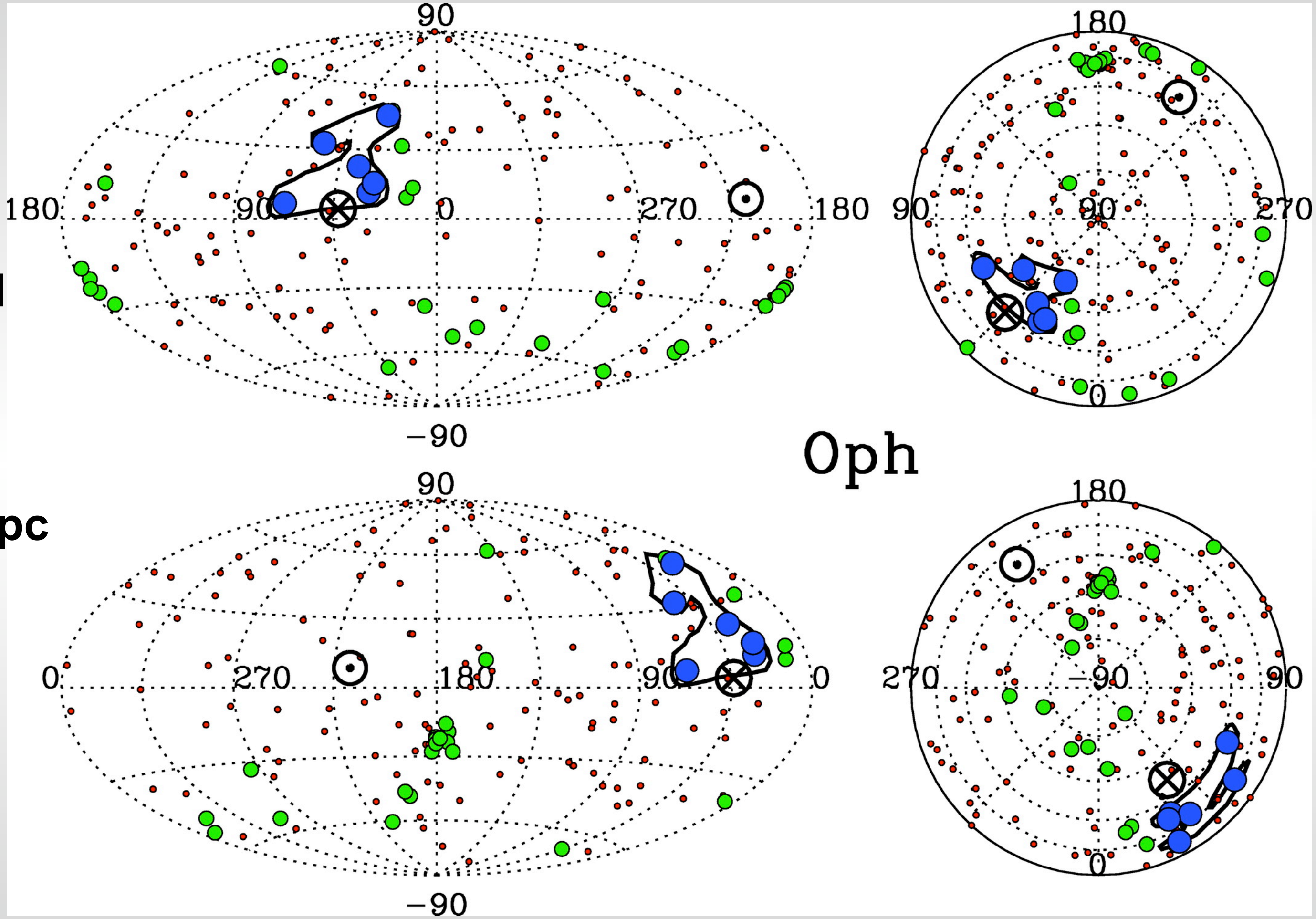

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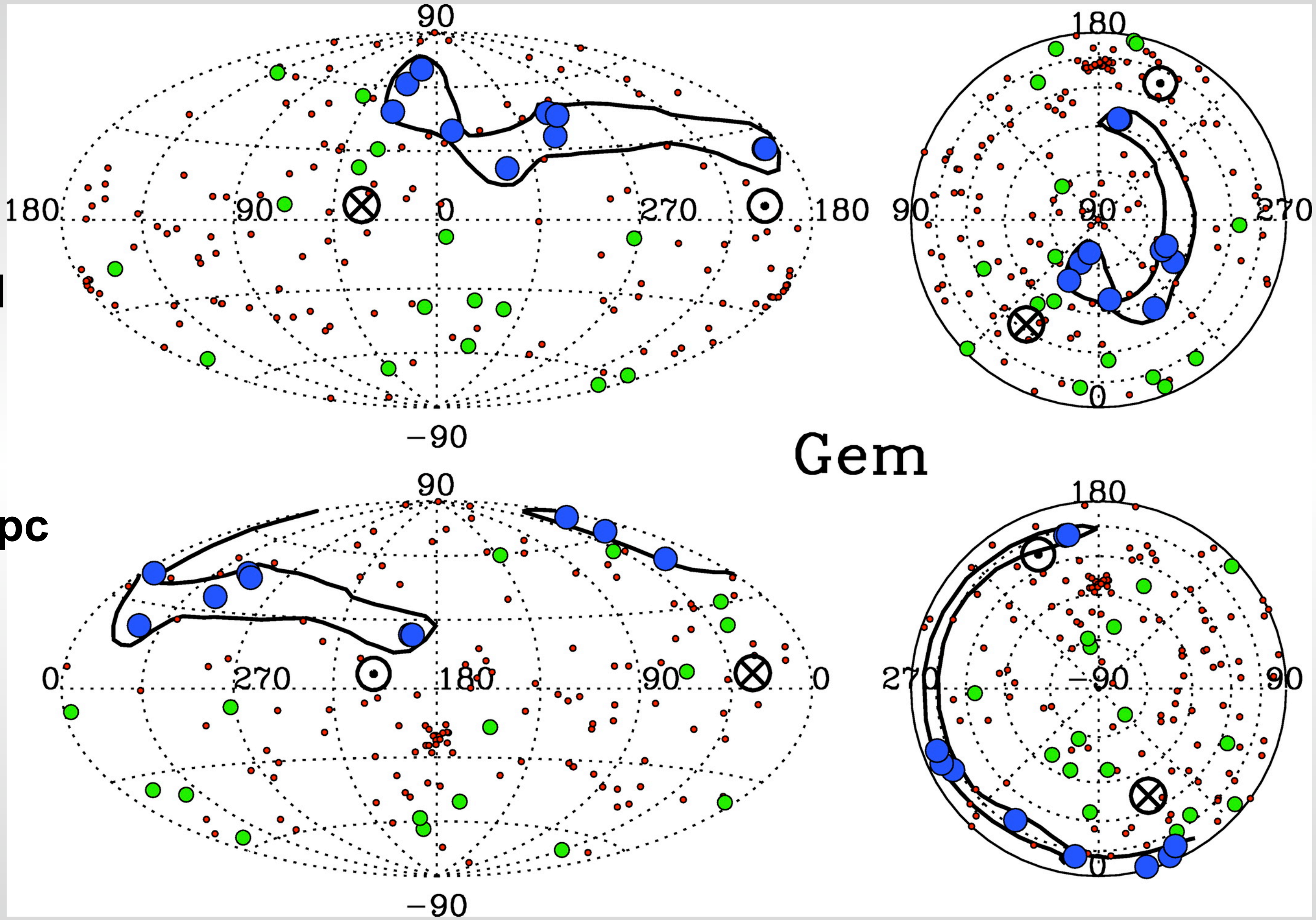
Closest star: 6.7 pc



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Local Clouds

Redfield & Linsky,
2008, ApJ, 673, 283

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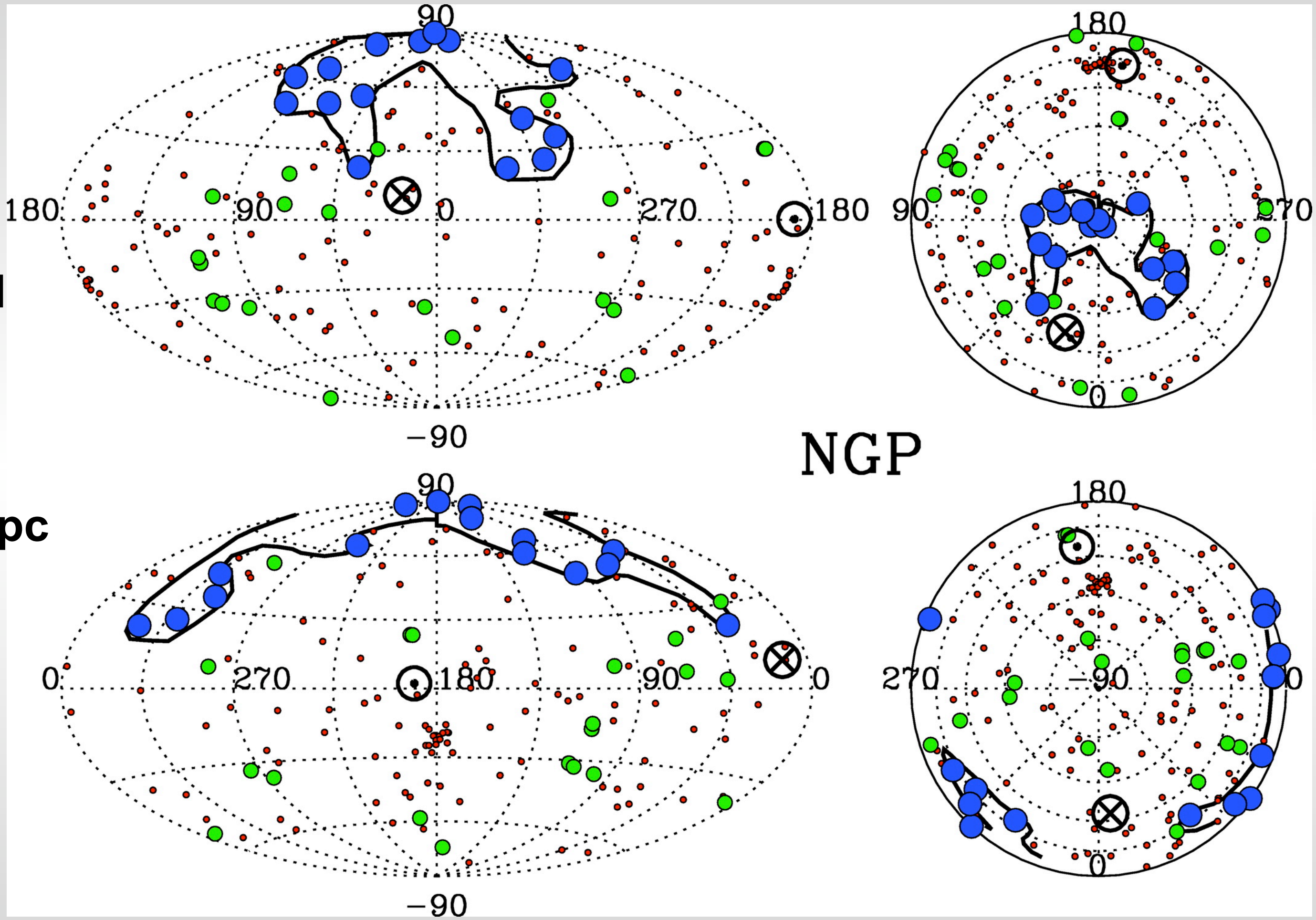
⊙ **Downwind direction**

Closest star: 8.5 pc



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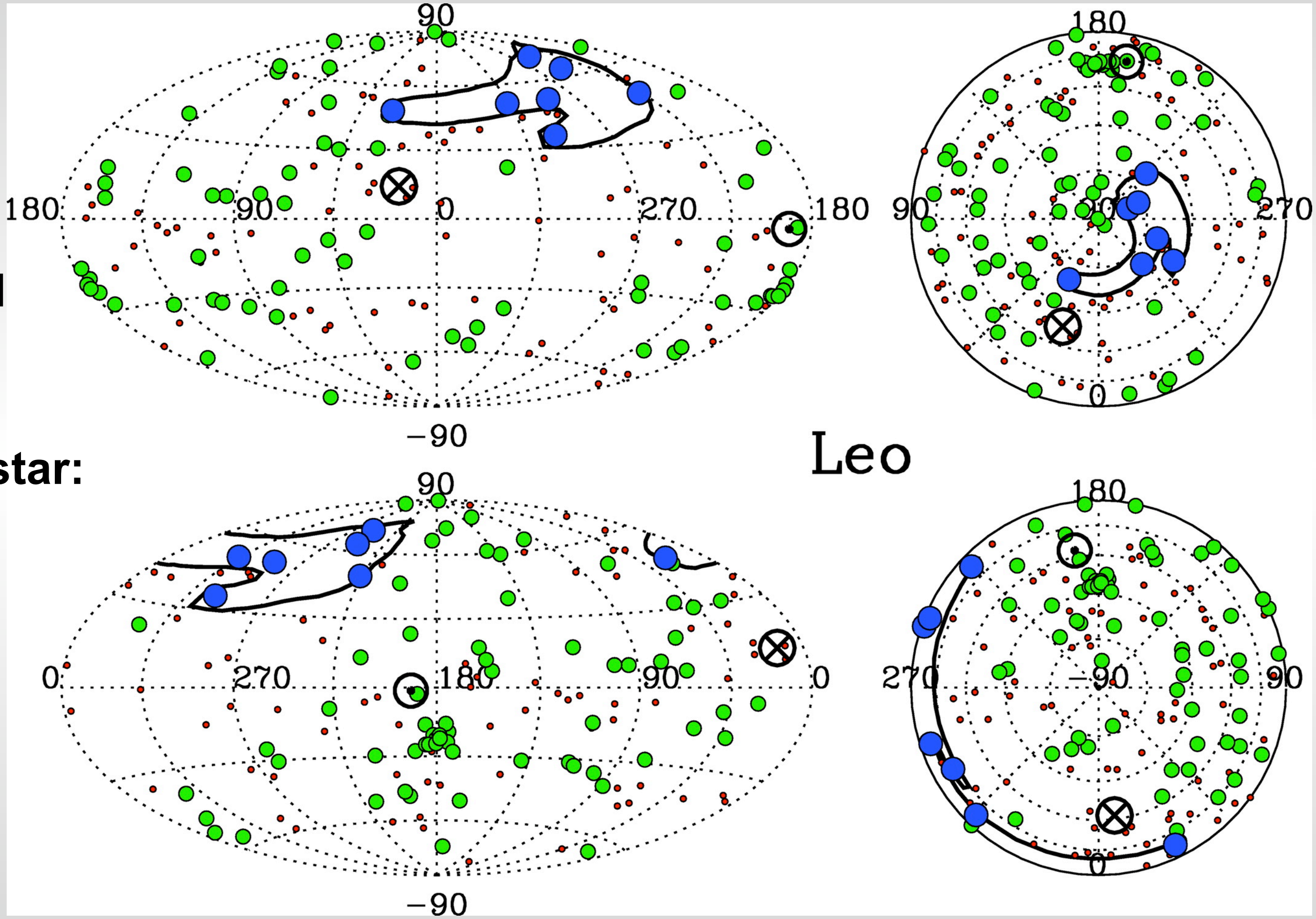
Closest star: 11.1 pc



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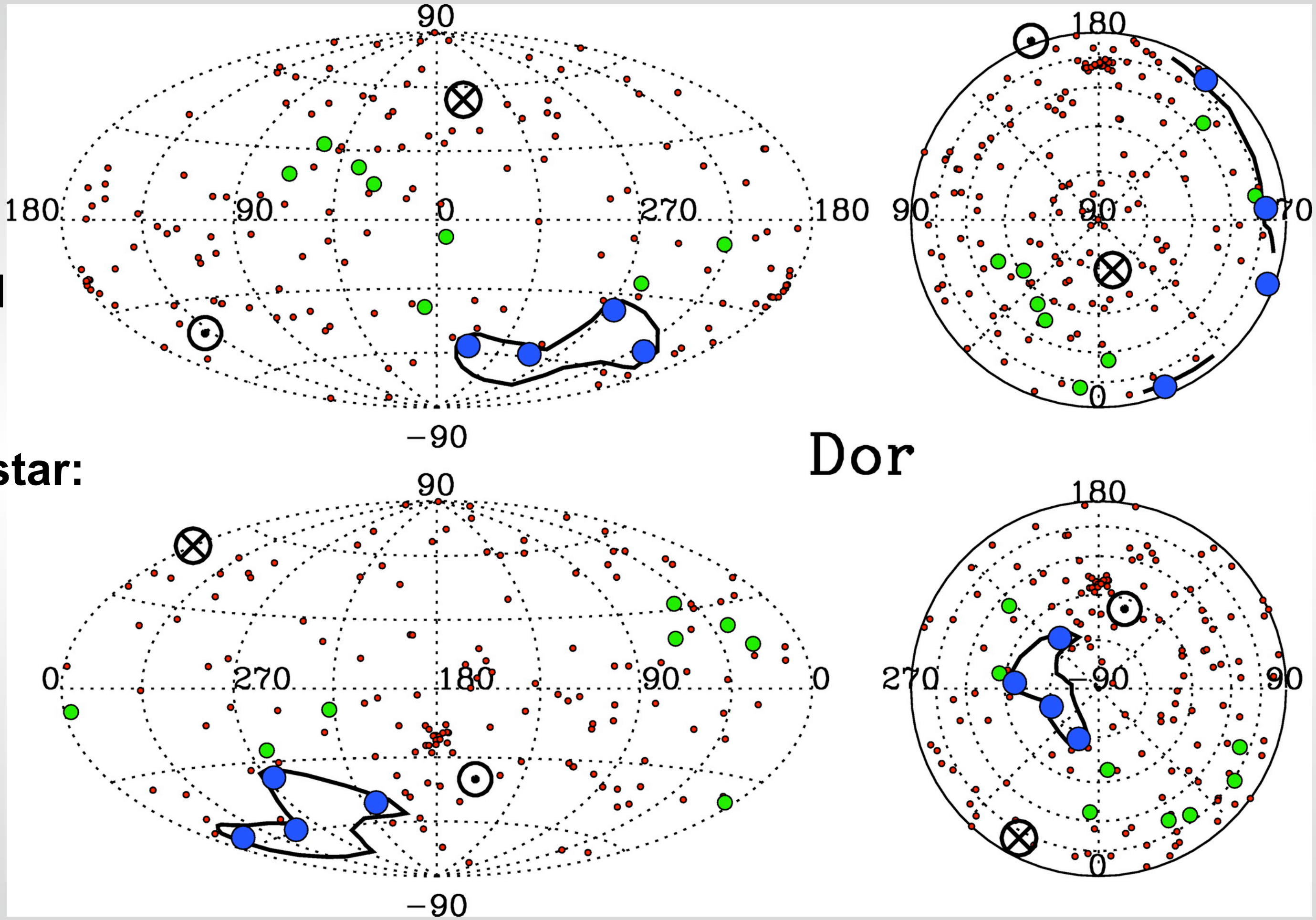

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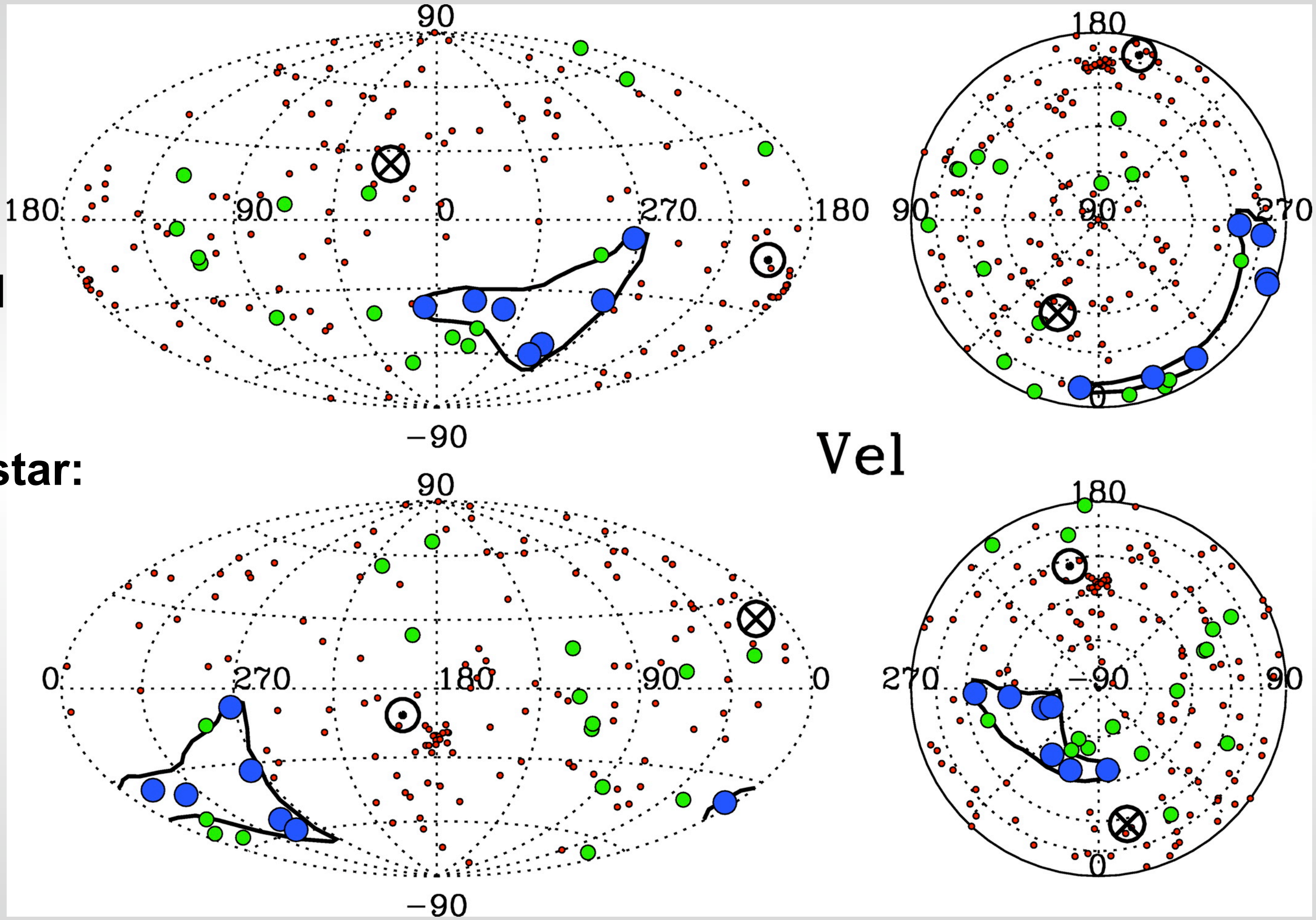
Closest star: 14.9 pc



Velocity comp. ident. with cloud and used to calculate *v*

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Entirely wrong velocity

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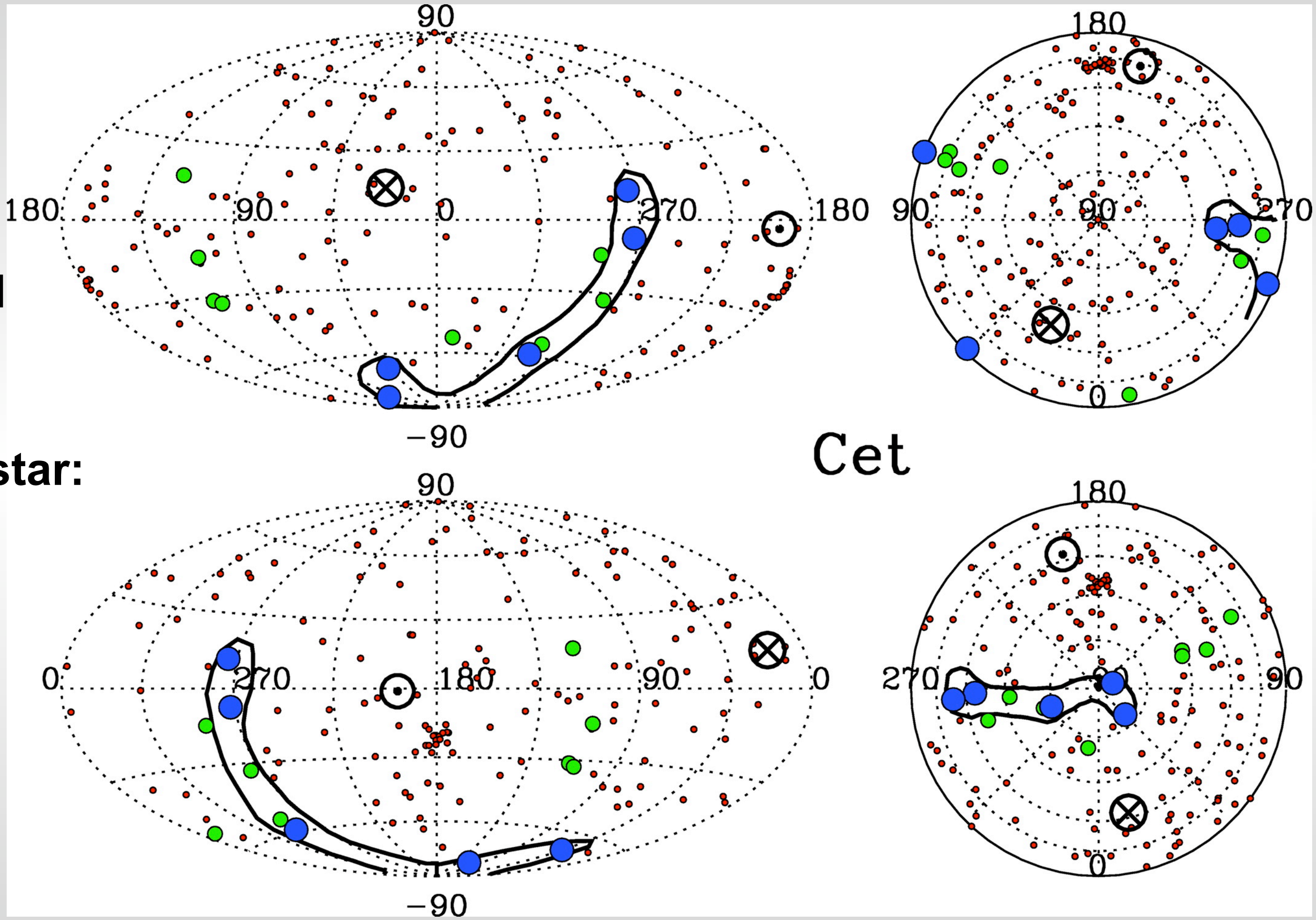
Redfield & Linsky, 2008, ApJ, 673, 283

⊗ **Upwind direction**

⊙ **Downwind direction**

Closest star: 15.5 pc



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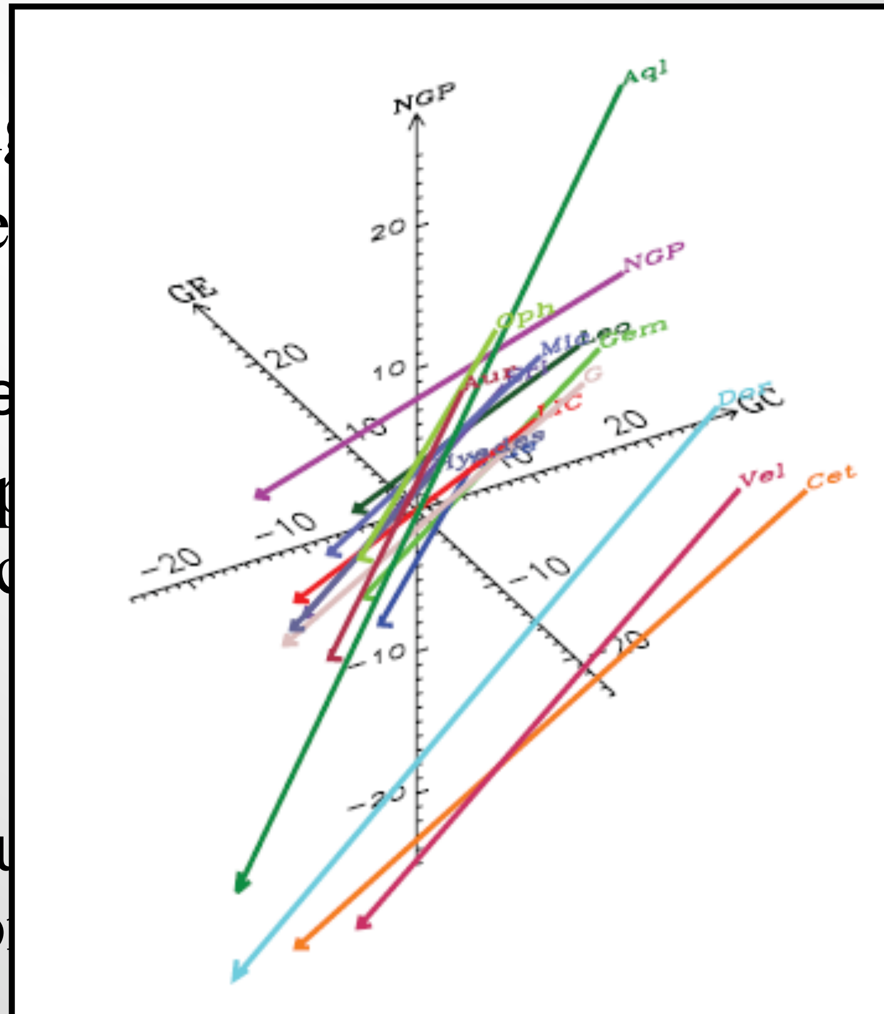
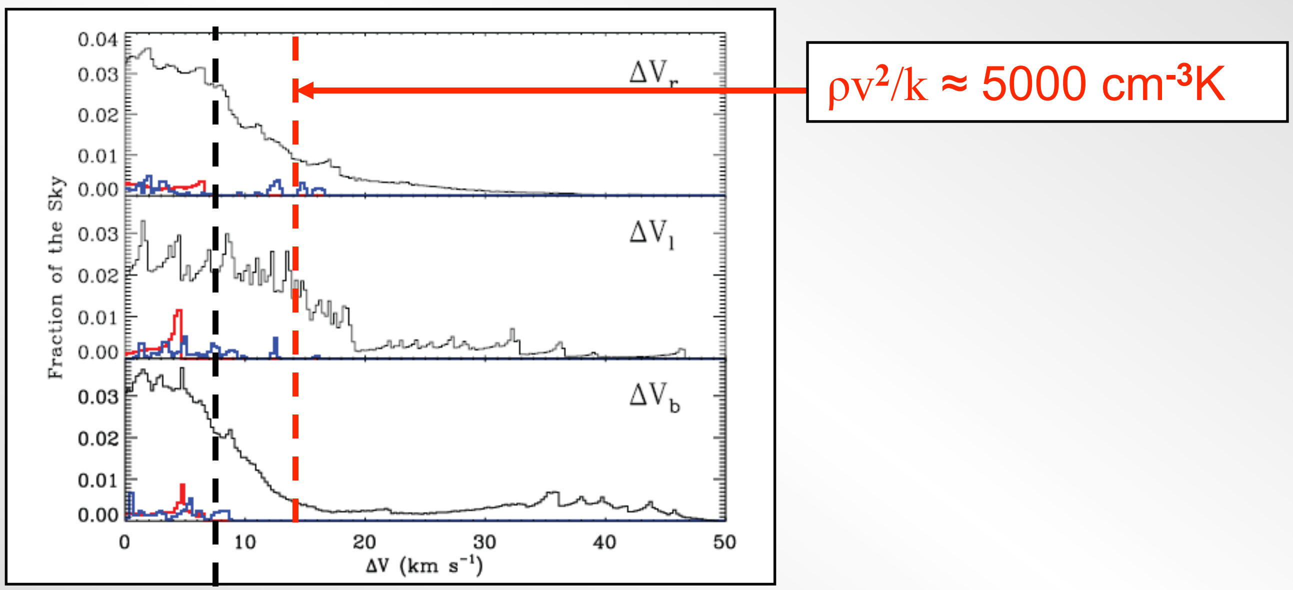
Conclusions about the Local Clouds



- Volume fillin ... 19%
- What's betwe ... hey confined?
  - Probably ve
- For the most p ... are a common direc
- Nevertheless, ... rsonic and the clouds cou ... er, creating interaction zo ... dentity

Conclusions about the Local Clouds

- Cloud interactions are difficult to identify specifically, but velocity differences in general terms can be calculated:



Typical sound speed in clouds

Fundamental Issues

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Temperatures and Turbulent Velocity Dispersions

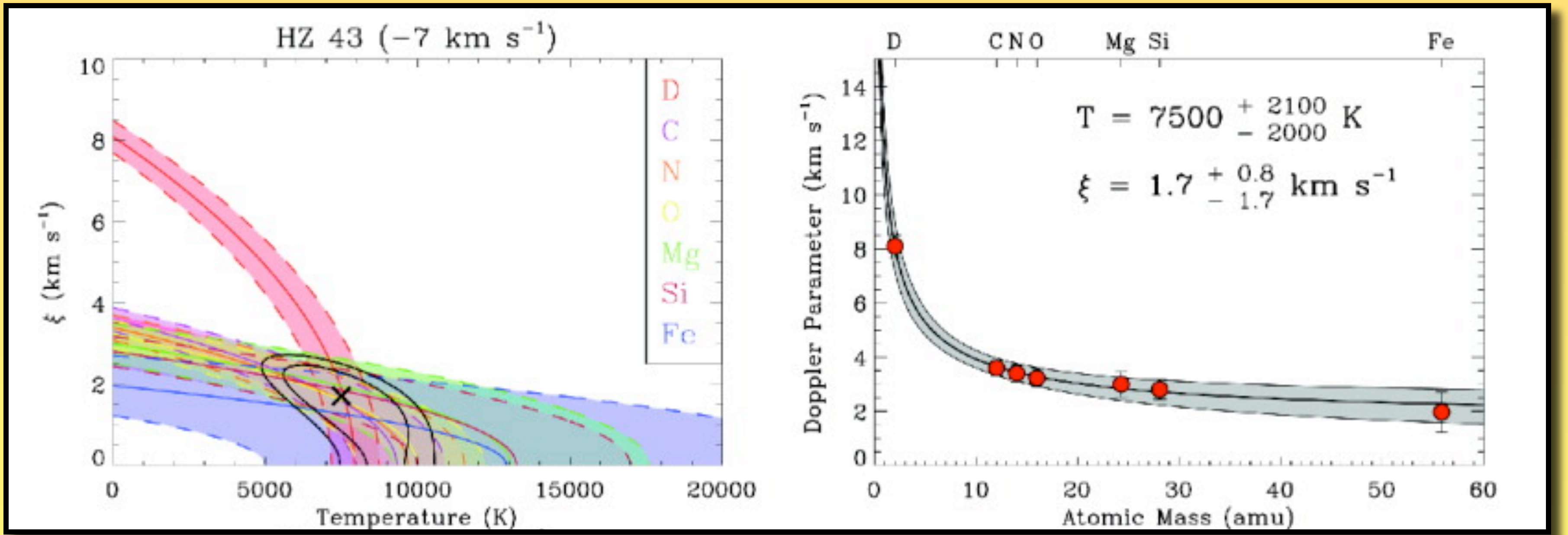
- Basic Formula – Doppler velocity dispersion adds in quadrature with turbulent velocities:

$$\boxed{b^2 = \frac{2kT}{m} + \xi^2 = 0.016629\frac{T}{A} + \xi^2}$$

This term varies with mass

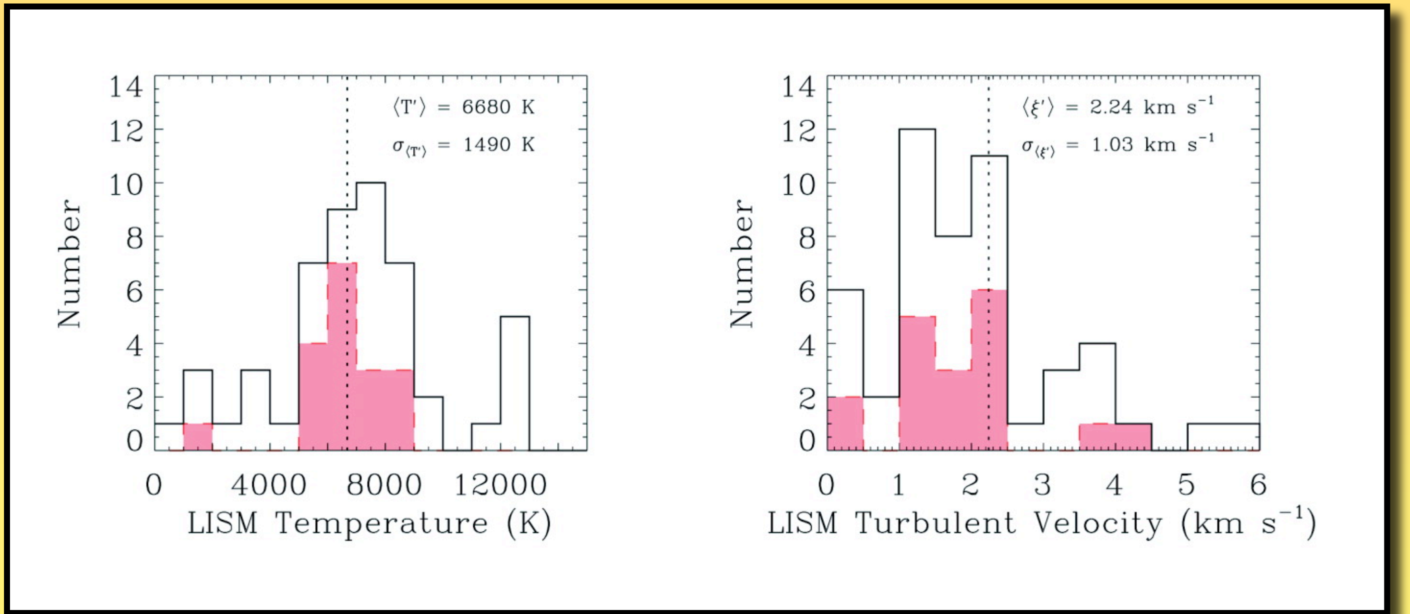
This one doesn't

Temperatures and Turbulent Velocity Dispersions



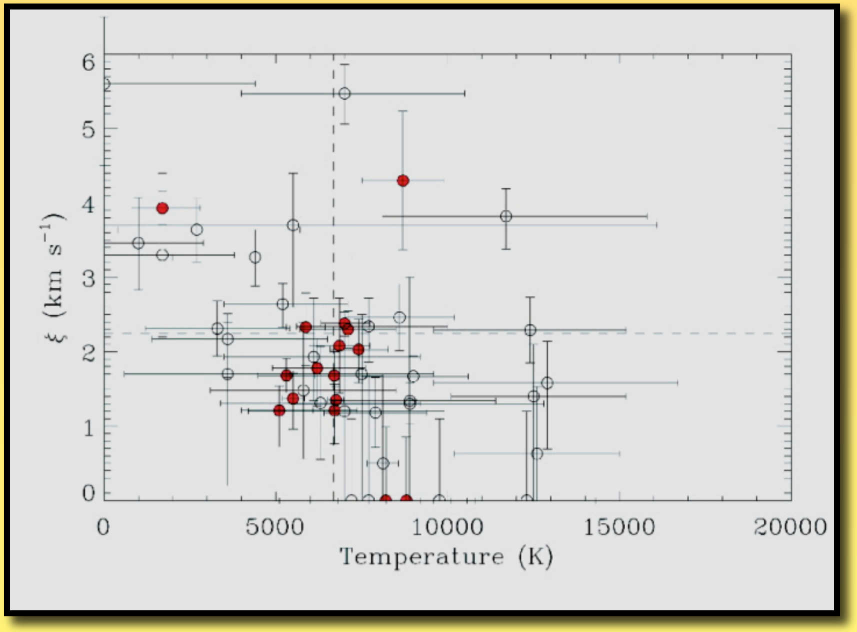
Redfield & Linsky (2004), ApJ, 613, 1004

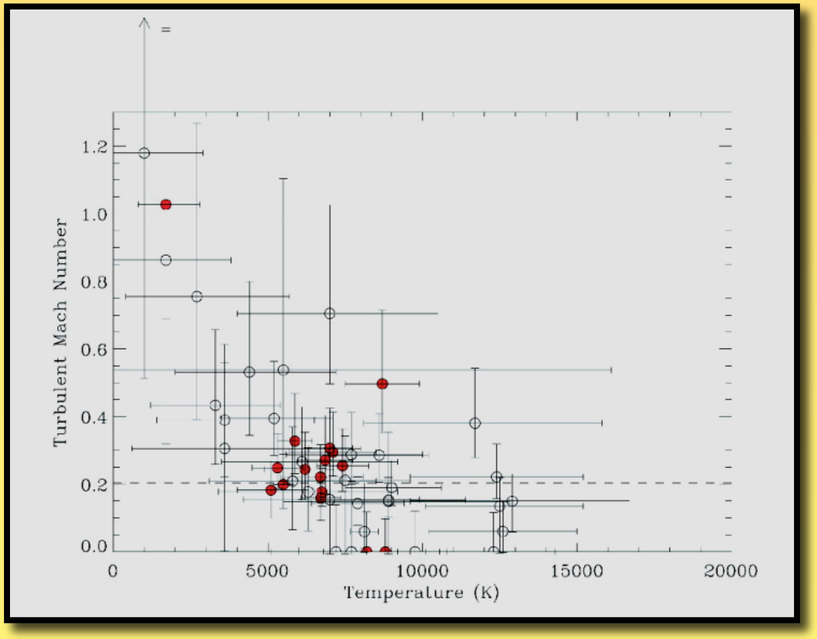
Temperatures and Turbulent Velocity Dispersions



Red portions indicate more precise measurements, i.e., those with errors less than the overall dispersion

Temperatures and Turbulent Velocity Dispersions



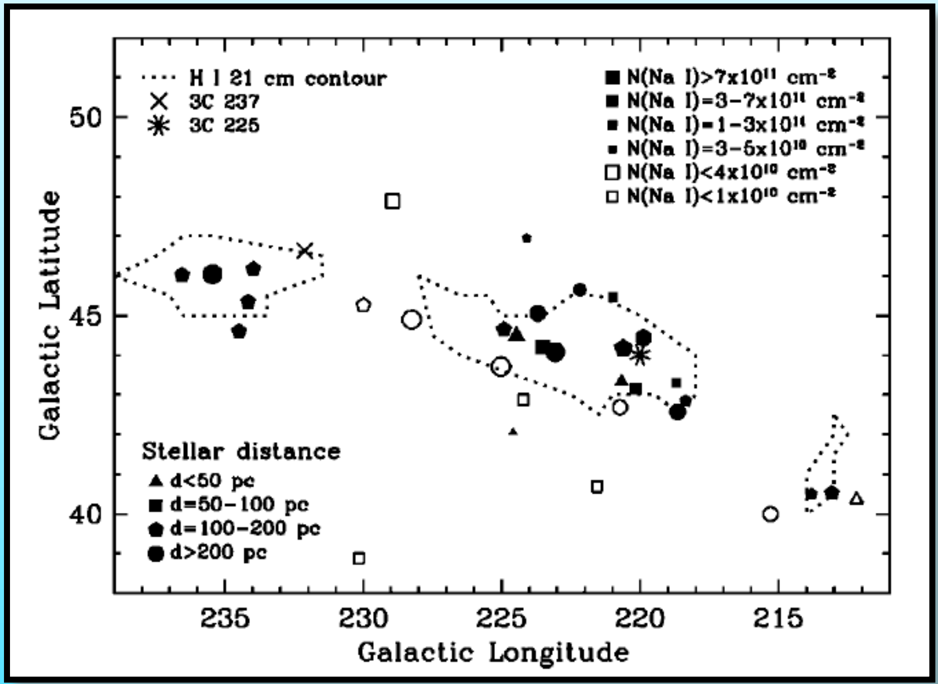


Temperatures and Turbulent Velocity Dispersions

However, there’s an interesting exception to this picture ….

A Very Cold Cloud

- Observed in absorption at 21-cm & Na I
- Distance < 45 pc, hence within the LB
- Extraordinarily cold: *T* = 20 (+6, -8) K
- Very thin if in normal pressure equilibrium with LB surroundings



Meyer et al. (2006), ApJ, 650, L67

Thermal Equilibrium

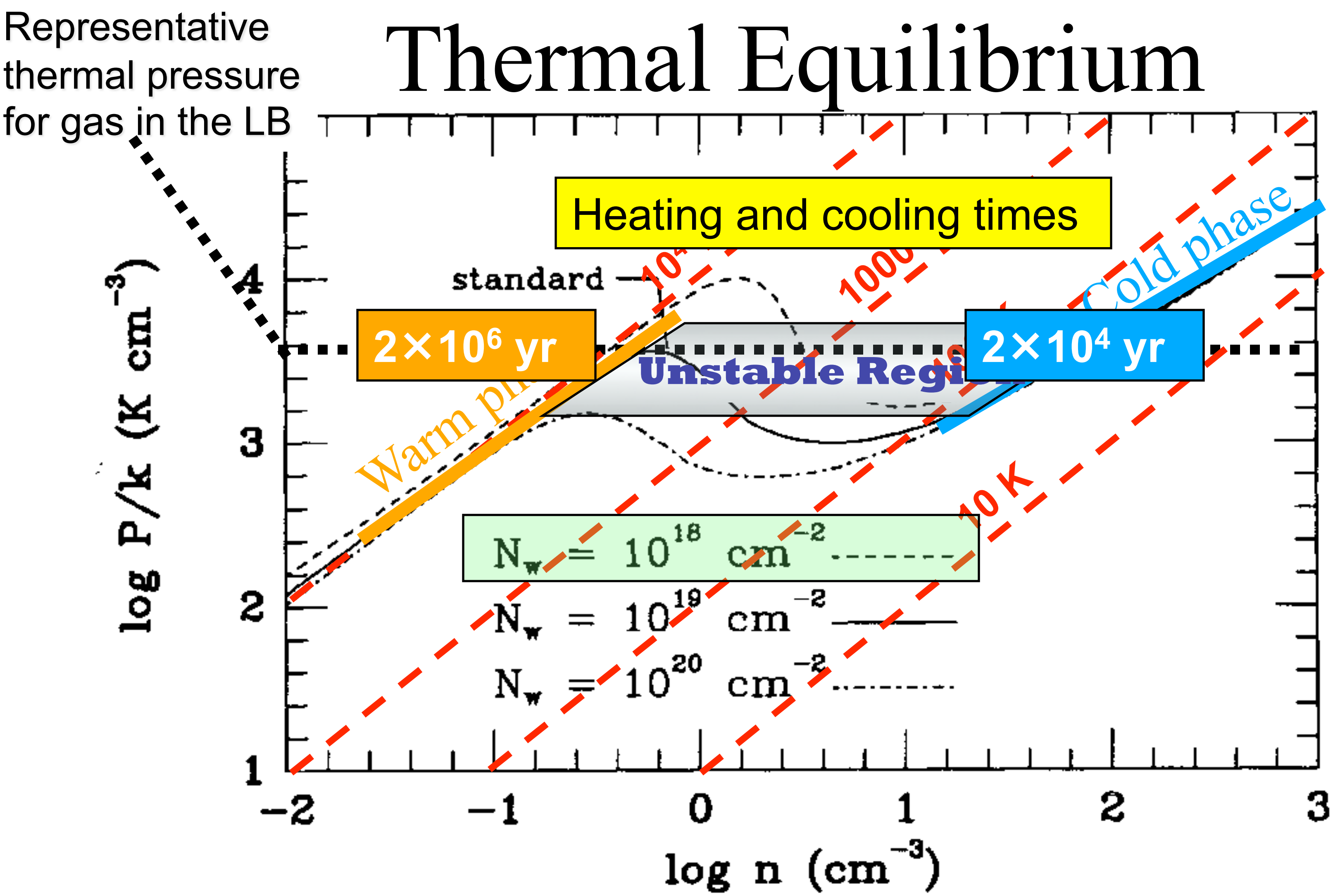


FIG. 4.—Thermal pressure P/k for various absorbing columns N_w. Curves are shown for P/k vs. hydrogen density n for $N_w = 10^{18}$ cm^{-2} (*dash*), $N_w = 10^{19}$ cm^{-2} (*solid*), and $N_w = 10^{20}$ cm^{-2} (*dash-dot*).

(Wolfire, Hollenbach, McKee, Tielens & Bakes 1995: ApJ, 443, 152.)

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Densities — **Easiest quantity to measure: n_e**

Compositions — Apportionment of elements in gas phase vs. dust

Ionization fractions — Density of ionizing radiation, history of the gas (ionization/recombination time scale)

Fine-structure Level Populations

- Simple equilibrium equation for a 2-level ground state of atom or ion X that has an excited level X^*:
  - $(n_e\gamma_{12e} + n_H\,\gamma_{12H})n(X) = (A_{21} \cancel{+ n_e\gamma_{21e} + n_H\gamma_{21H}})n(X^*)$
  - **For either case (collisions with electrons or H)**
    $\gamma_{12} = (g_1/g_2)\gamma_{21}\boxed{\exp[\,-(\Delta E/kT)]}$ **≈ 1 for T > several × 10^3 K**
  - **Usually,** $n_e\gamma_{21e}$ **and** $n_H\gamma_{21H} \ll A_{21}$
  - **Electrons:**
    - γ_{21e} **= (slowly varying const vs. *T*) × $T^{-0.5}$**
  - **Hydrogen atoms:**
    - γ_{21H} **is more arbitrary**

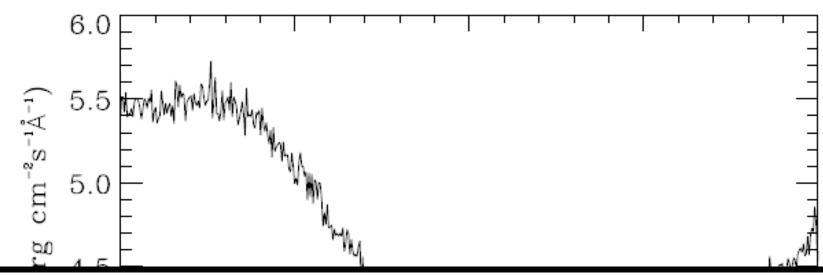
Fine-structure Level Populations

- **As a rule, the $n_e\gamma_{12e}$ term is important for ions, while the $n_H\,\gamma_{12H}$ term is important for neutrals**

- Available species with fine-structure splittings

Atoms	**Ions**
C I (very weak, but detectable under favorable circumstances)♪	
O I (even weaker)♪	

C I Fine-structure Excitation



the C I fine-structure populations indicate that for the clouds in front of γ Ori, δ Cyg, and α Del, $10^3\ \mathrm{cm}^{-3}\ \mathrm{K} < p/k < 10^4\ \mathrm{cm}^{-3}\ \mathrm{K}$ at about the $\pm 1\ \sigma$ confidence level in each case.

FIG. 3.—Spectrum of δ Cyg covering the 1560 Å multiplet of C I. The strong absorption feature is from the 1560.309 Å transition of C I, while the weaker one arises from a blend of two features from C I* at 1560.682 and 1560.709 Å.

Jenkins (2002) ApJ, 580, 938

Fine-structure Level Populations

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Atoms

C I (very weak, but detectable under favorable circumstances)♪

O I (even weaker)♪

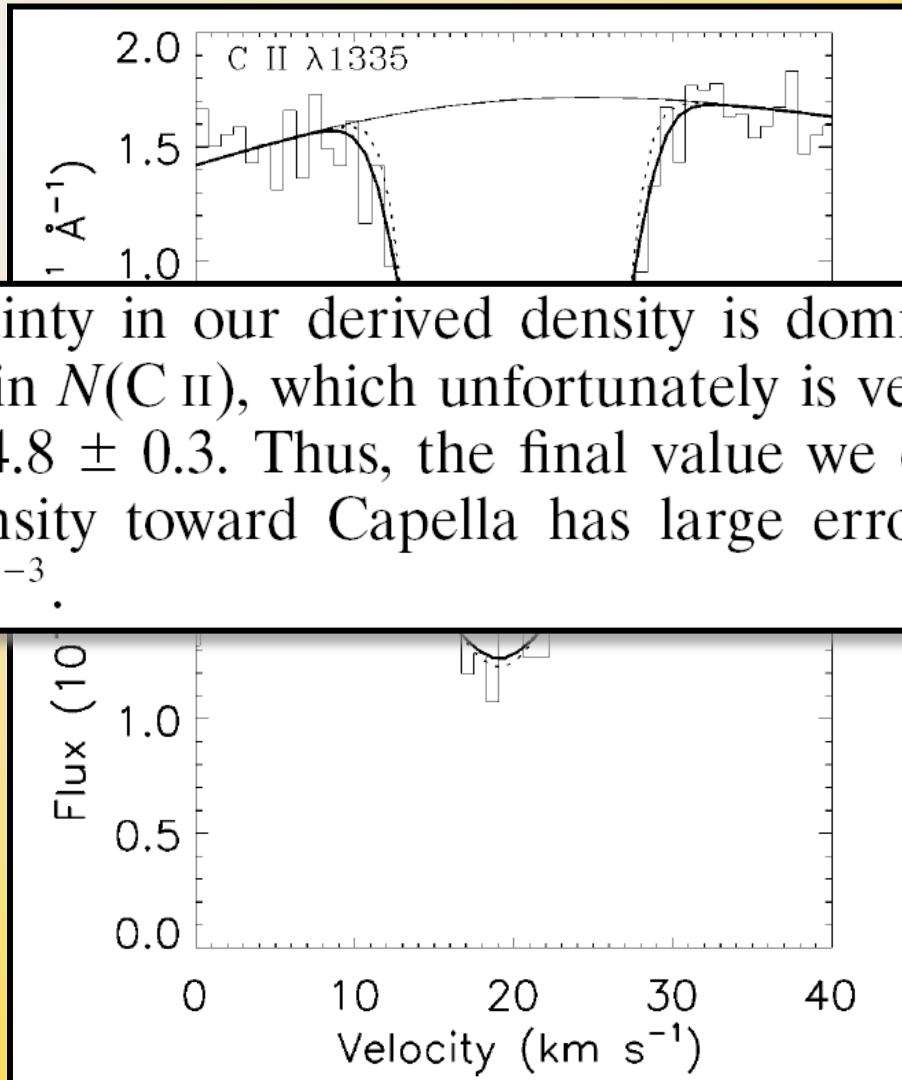
Ions

Si II, Fe II (excited levels too weak to see in LISM)♪

C II is good, although absorptions out of the unexcited level are always saturated♪

First Measurement of C II* and C II

Line of sight to Capella (α Aur) over a distance of 13 p



The uncertainty in our derived density is dominated by the uncertainty in N(C II), which unfortunately is very large—log N(C II) = 14.8 ± 0.3. Thus, the final value we quote for the electron density toward Capella has large error bars: $n_e = 0.11^{+0.12}_{-0.06}$ cm^{-3}.

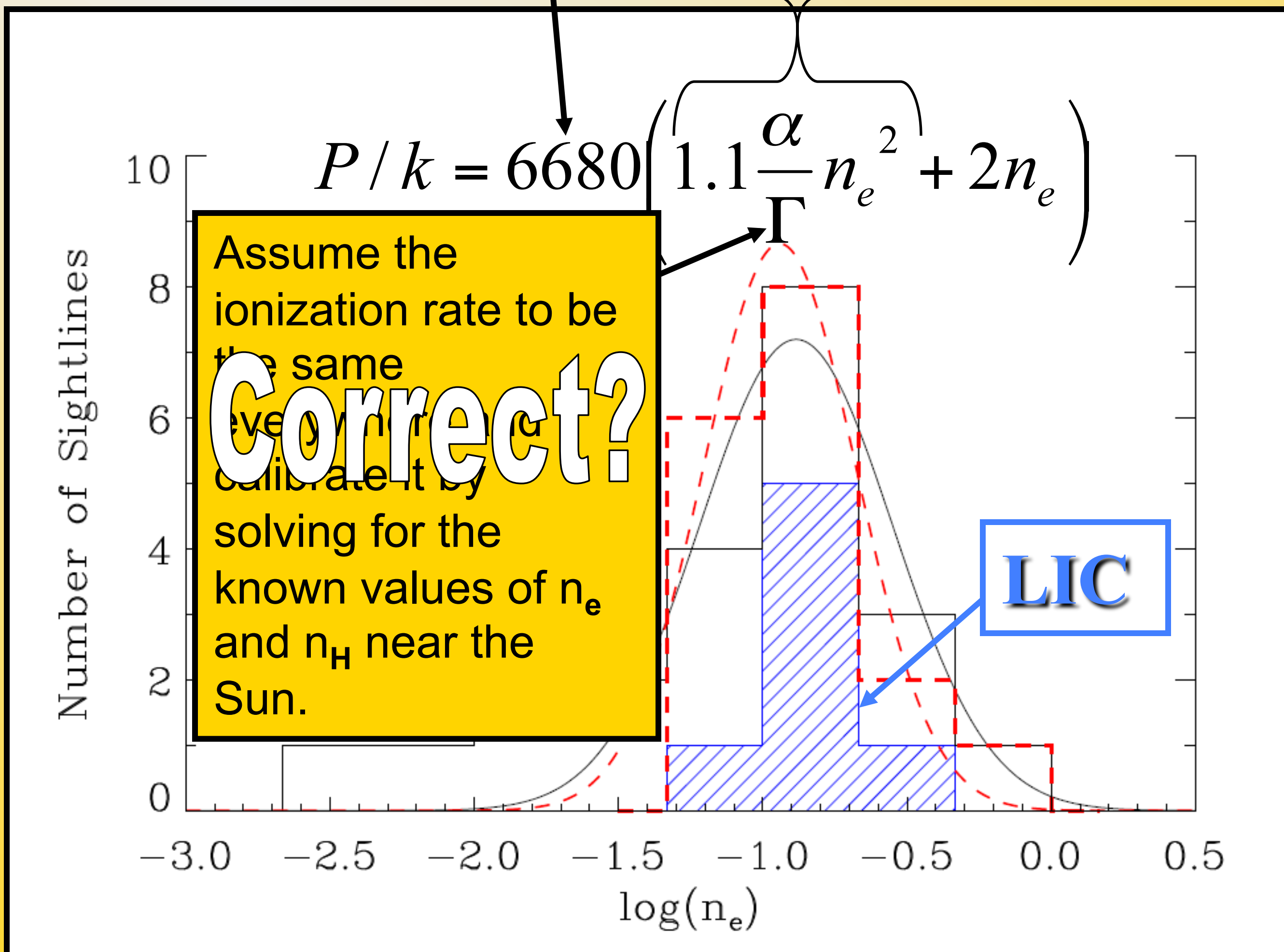
Wood & Linsky (1997), ApJ, 474 L39

A Way to Overcome the C II Saturation Problem

- Use S II as a surrogate for C II – S II lines are not badly saturated and there are 3 lines of different strength available.
- *Assume* that we know the true ratio of S to C in the gas, but be open to the possibility that this is not true.

Measurements of n_e

$$P/k = \overbrace{6680}^{T}\left(\overbrace{1.1\frac{\alpha}{\Gamma}n_e^{2} + 2n_e}^{n_H + n_{He}}\right)$$



Assume the ionization rate to be the same everywhere and calibrate it by solving for the known values of n_e and n_H near the Sun.

Correct?

Redfield & Falcon (2008), arXiv 0804.1802

Ionization Equilibrium

- Most suitable element to study is Mg
- Relevant equation:

Photoionization — Dominant process

Collisional ionization — Negligible

Charge exchange — Small effect

Ionization

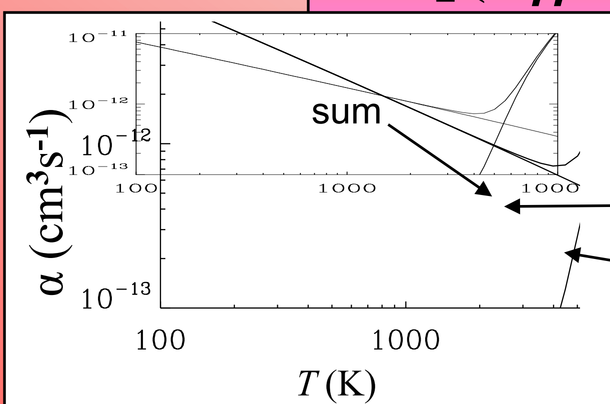
$$(\Gamma + n_e C_e + n_{\mathbf{H+}} \mathrm{C}_{\mathbf{X,H+}} + n_{\mathbf{He+}} \mathrm{C}_{\mathbf{X,He+}})\, n(\mathrm{Mg\ I}) = [(\alpha_{rr} + \alpha_{di}) n_e + \alpha_g n_{\mathbf{H}}]\, n(\mathrm{Mg\ II})$$

Recombination

Recomb. dust grains — Very minor effect for LISM

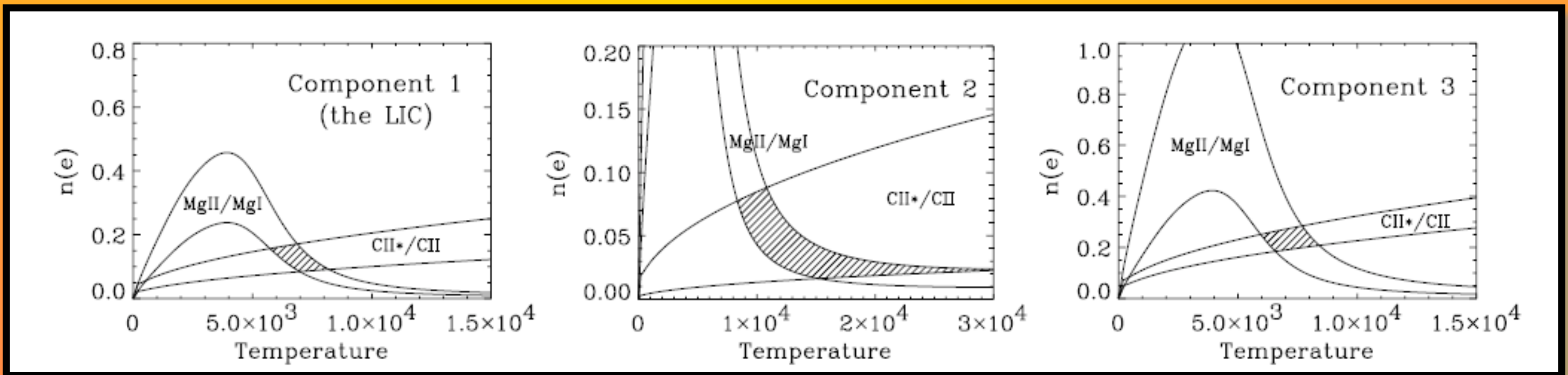
Dielectronic recomb. — Strong onset for T > 5000 K

Radiative recomb. — Simple power law with T



Use Fine-structure Excitation and Ionization Equilibrium Together

- Three velocity components toward ε CMa



Gry & Jenkins (2001), A&A,367,617

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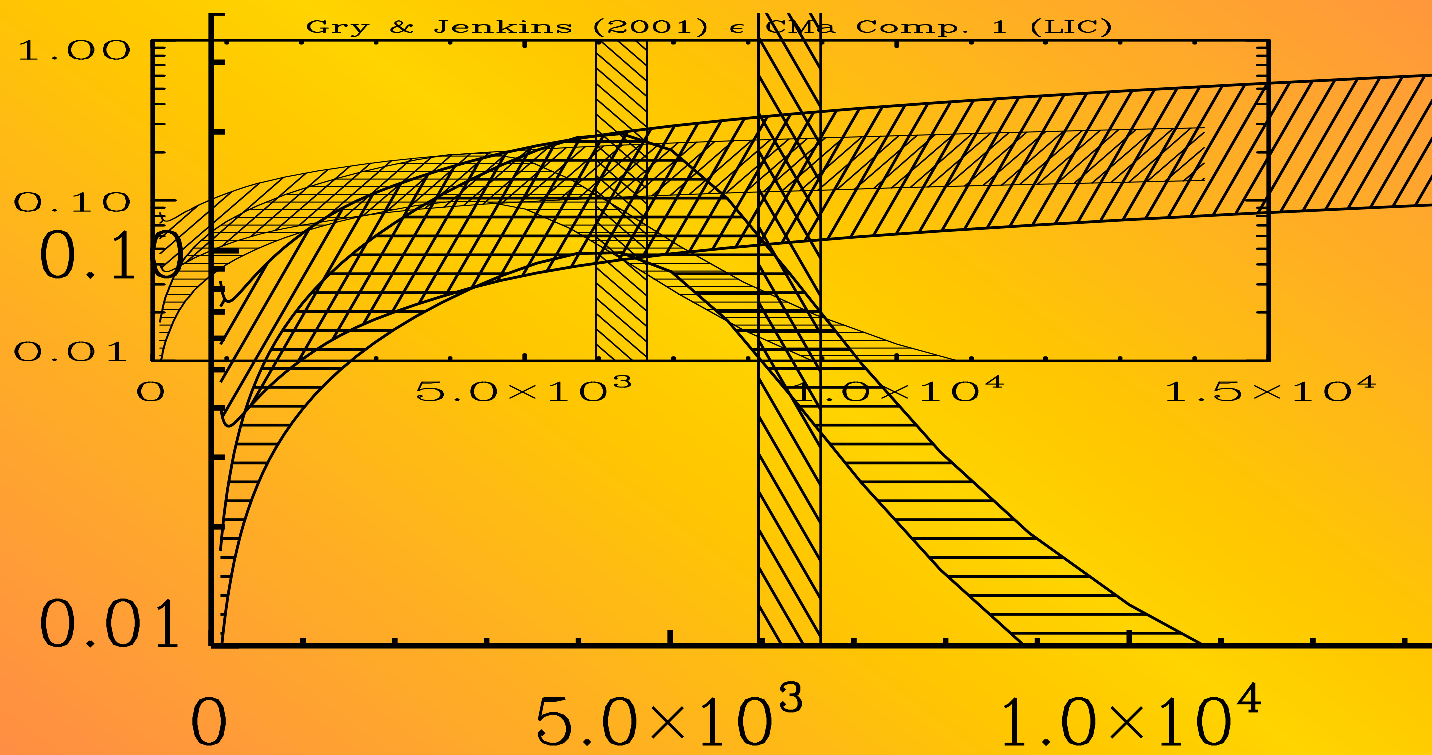
After a Revision of the Mg Dielectronic Recombination Rate

New results from Altun, et al. (2006) A&A, 447, 1165



Slavin & Frisch (2006), ApJ, 651, L37

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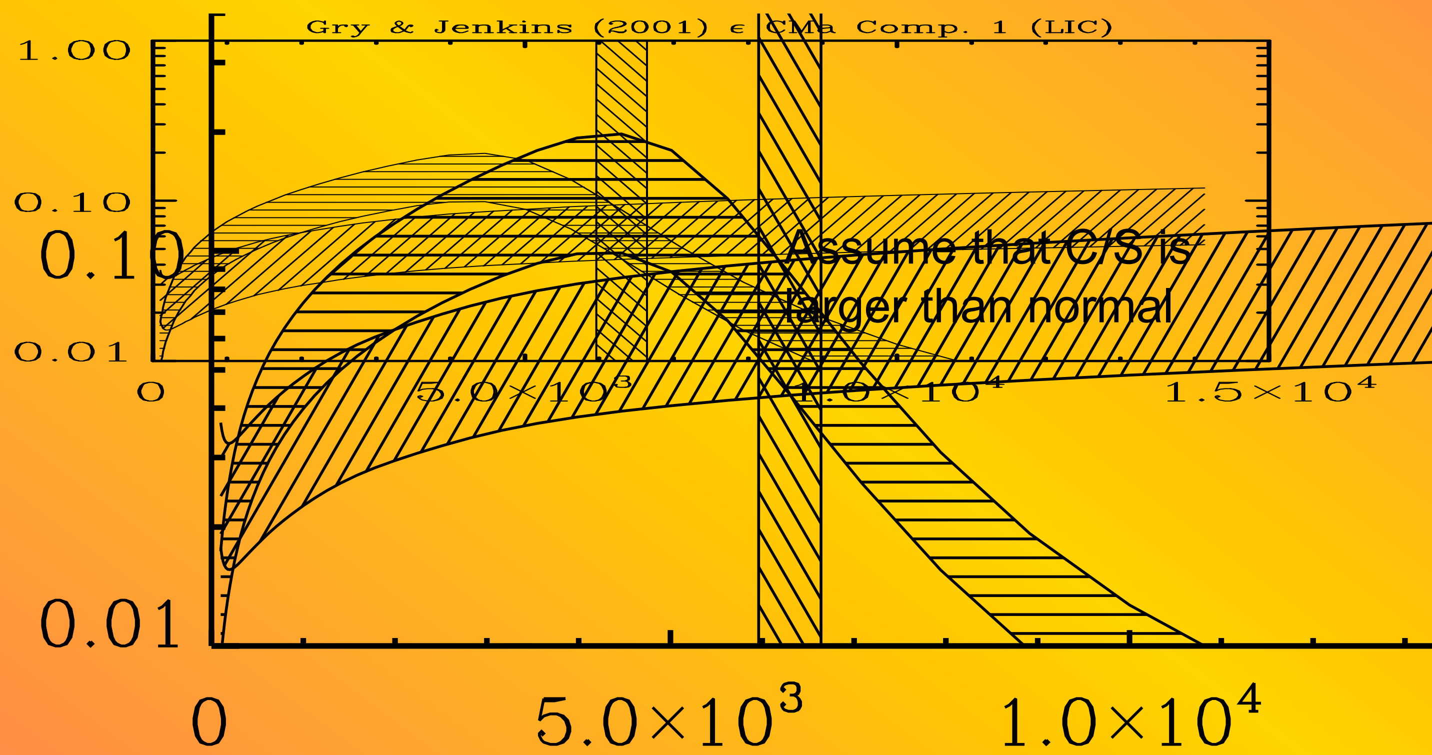


Slavin & Frisch (2006), ApJ, 651, L37

Flux Determination

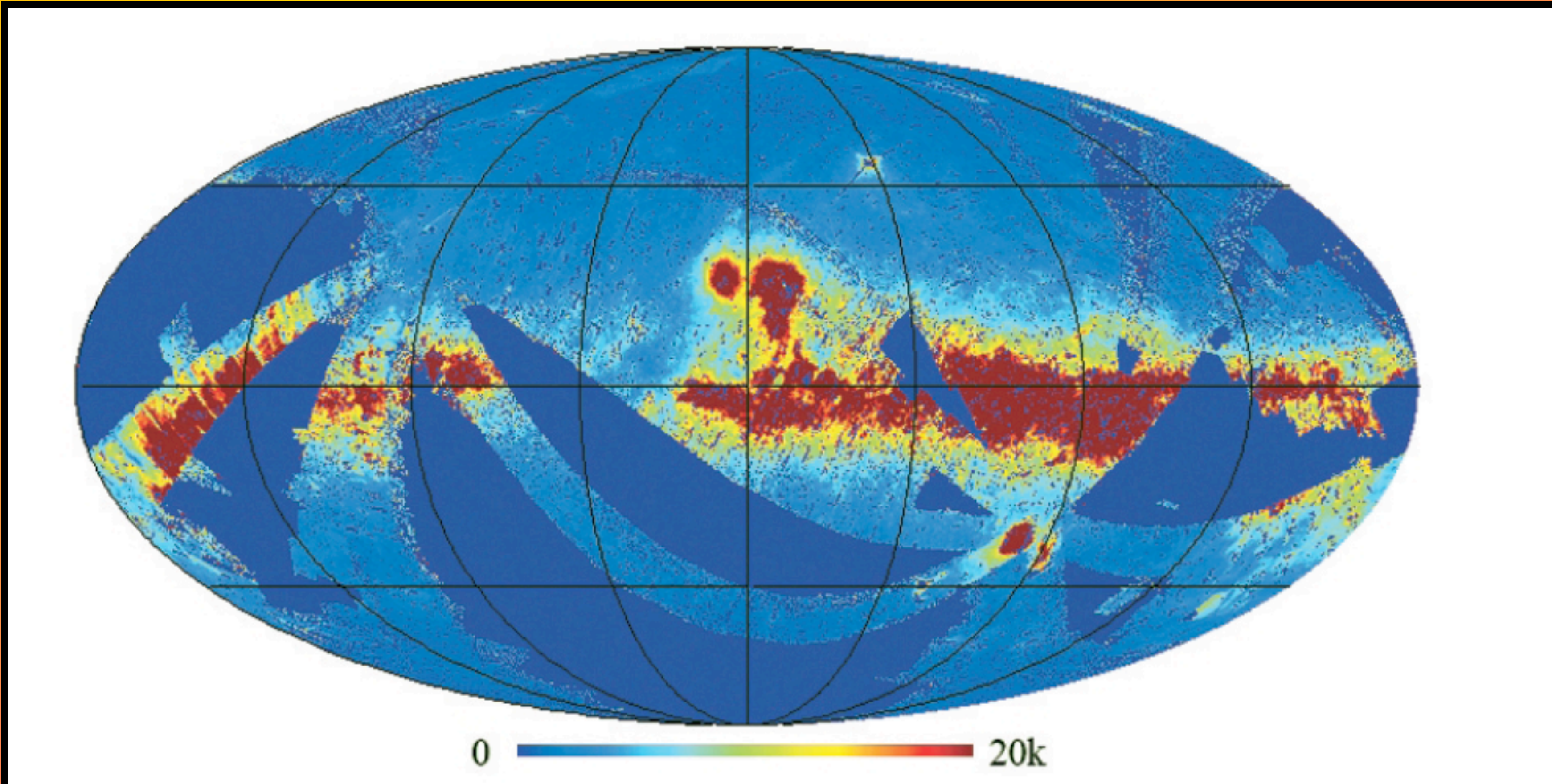
- **Results from the ultraviolet sky-survey telescope (S2/68) in the TD-1 satellite reported by Gondhalekar, Phillips & Wilson (1980):**

Table 5. Observed integrated ultraviolet flux from the whole sky in units of $10^{-7}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,\AA^{-1}}$

	Wavelength (Å)			
	2740	2365	1965	1565
Flux from unblended stars	3.92	5.40	7.77	10.61
Flux correction for blends	0.44	0.71	1.06	1.53
Total flux from direct starlight	4.36	6.11	8.83	12.14
Estimated flux from DGL	0.85	0.84	1.06	1.05
TOTAL flux (direct plus diffuse)	5.37	6.95	9.89	13.19

?

Diffuse Galactic Light for 1360 < λ < 1730 Å Measured by the SPEAR Mission



Edelstein et al. (2006), ApJ, 644, L153

Correction to Old Ionizing Flux Determination

- **Results from the ultraviolet sky-survey telescope (S2/68) in the TD-1 satellite reported by Gondhalekar, Phillips & Wilson (1980):**

Table 5. Observed integrated ultraviolet flux from the whole sky in units of 10^{-7} erg cm^{-2} s^{-1} Å^{-1}

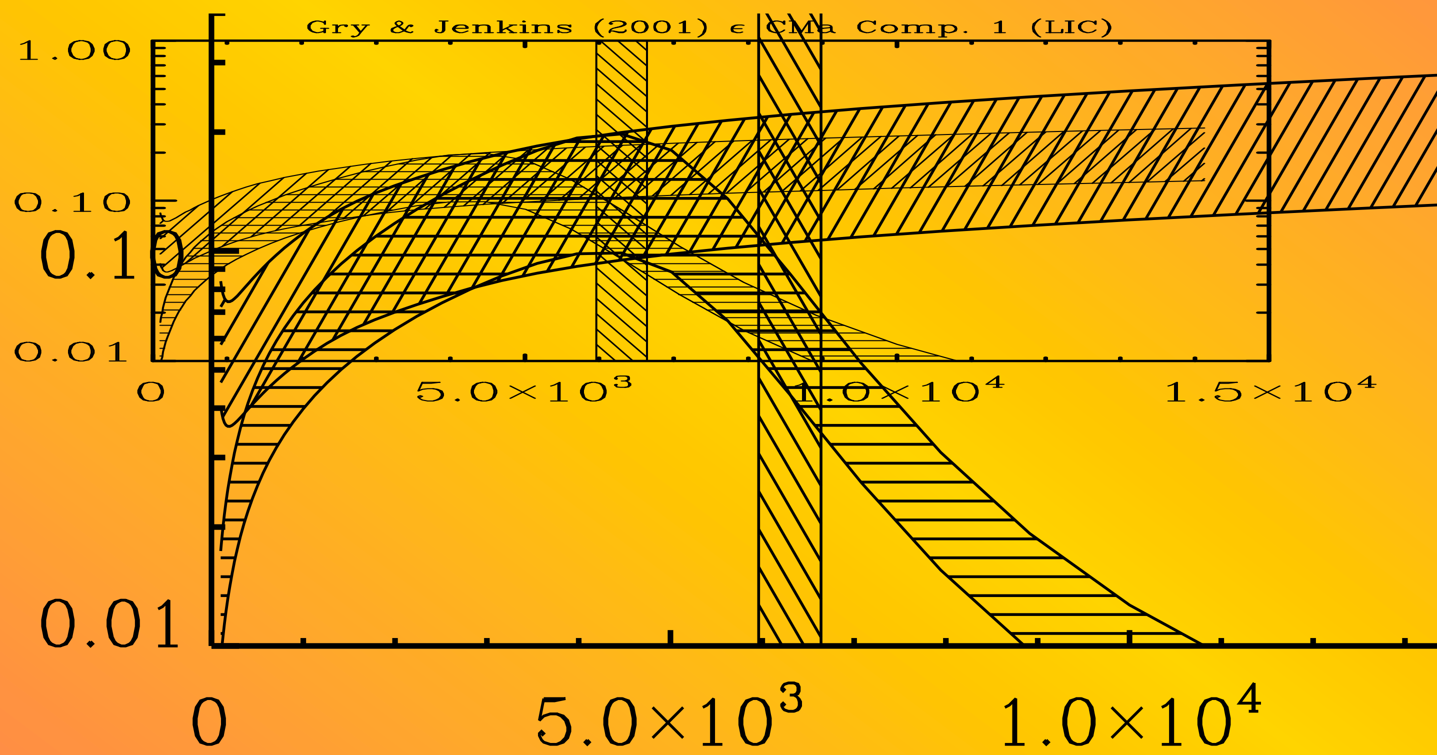
	Wavelength (Å)			
	2740	2365	1965	1565
Flux from unblended stars	3.92	5.40	7.77	10.61
Flux correction for blends	0.44	0.71	1.06	1.53
Total flux from direct starlight	4.36	6.11	8.83	12.14
Estimated flux from DGL	0.85	0.84	1.06	6.2 ~~1.05~~
TOTAL flux (direct plus diffuse)	5.37	6.95	9.89	18.3 ~~13.19~~

39% increase

How much here as well?

After a Revision of the Mg Dielectronic Recombination Rate

New results from Altun, et al. (2006) A&A, 447, 1165



Slavin & Frisch (2006), ApJ, 651, L37

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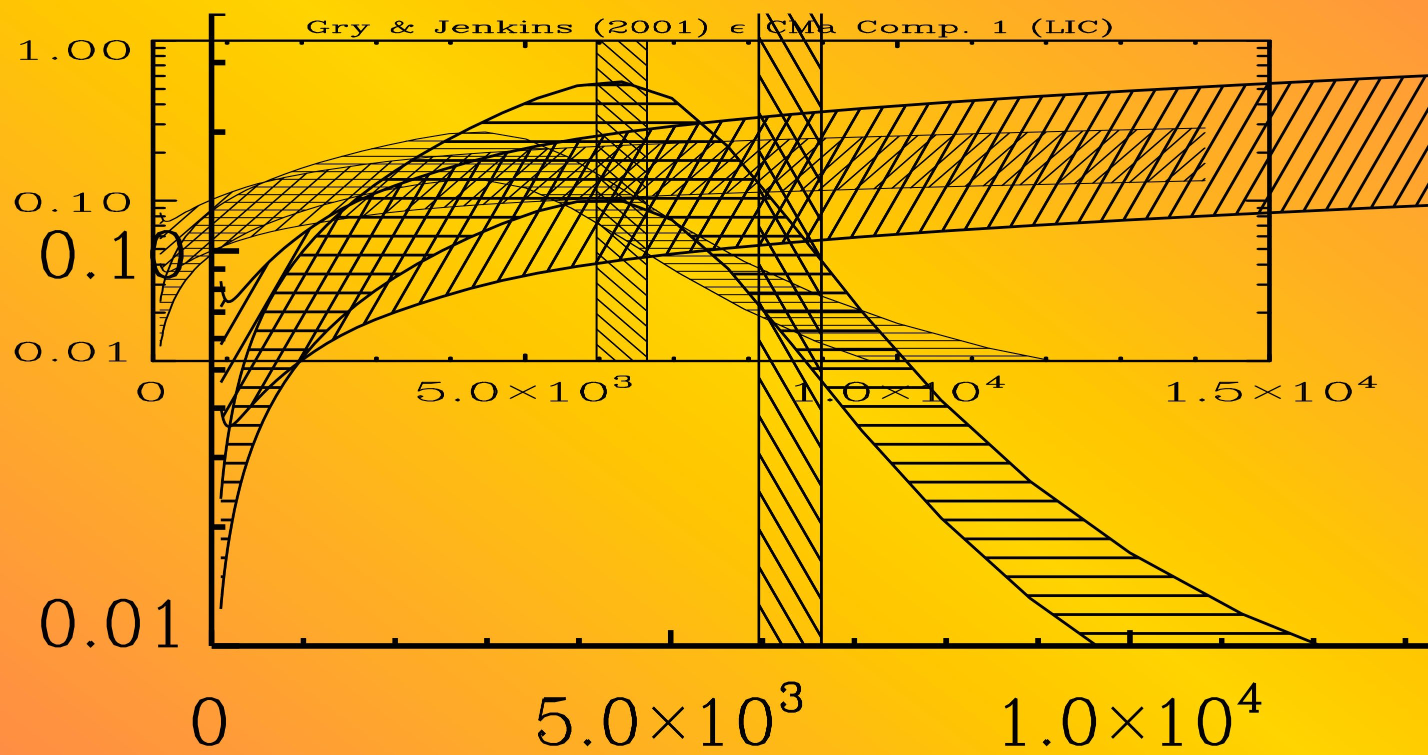
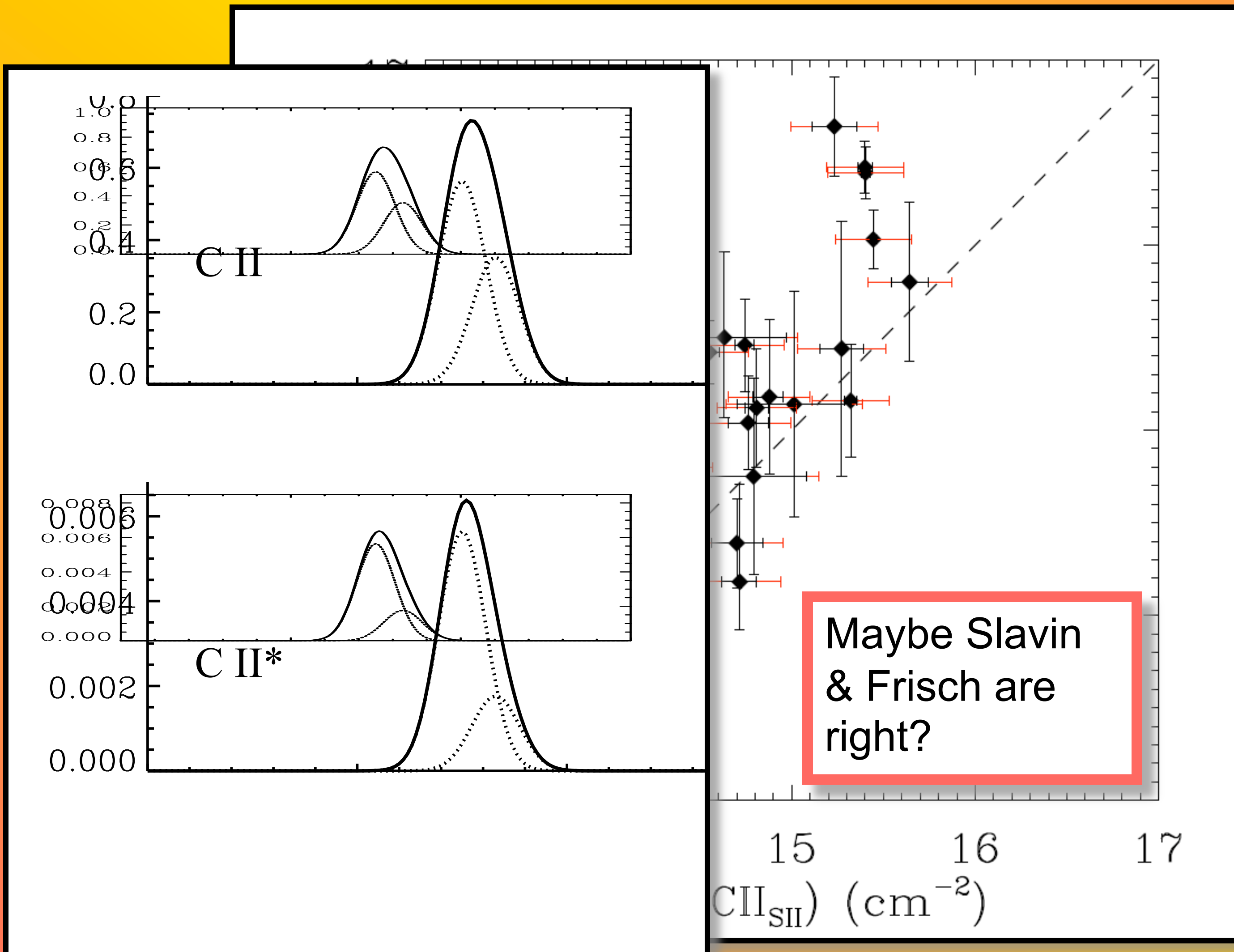


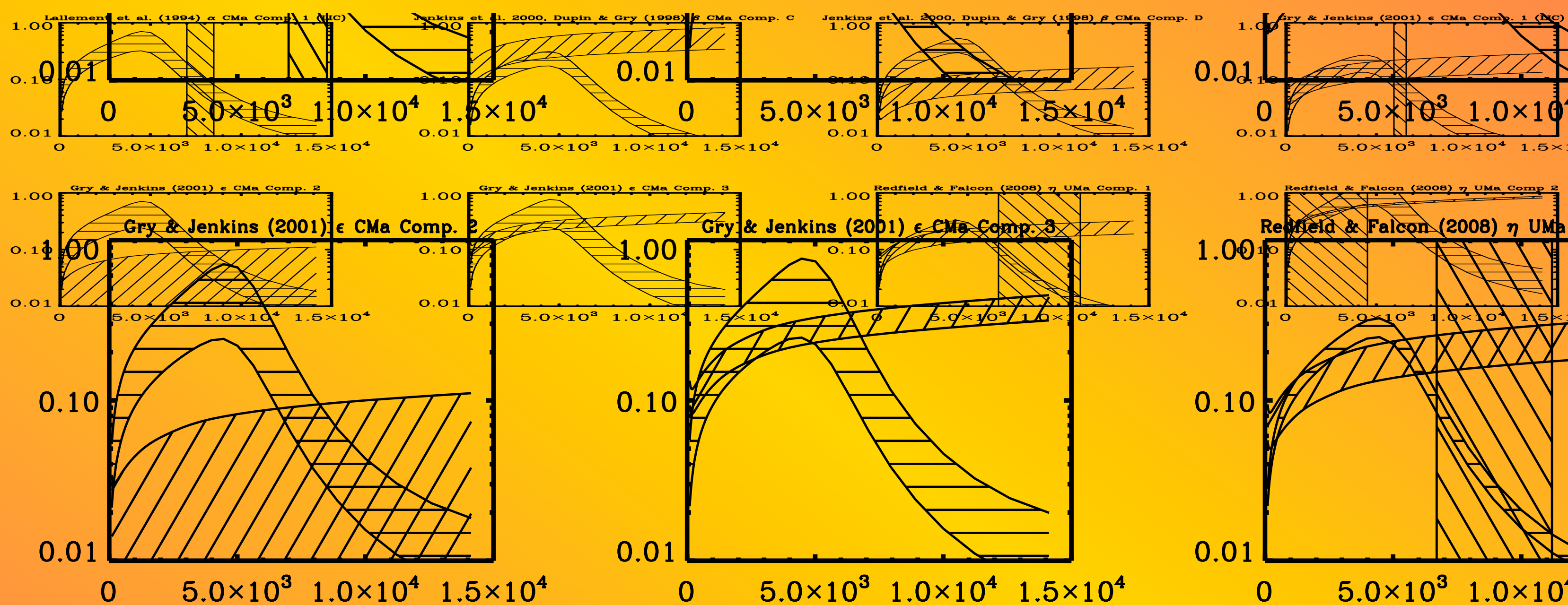
Slavin & Frisch (2006), ApJ, 651, L37

A Comparison Between C II Measured Directly and C II Inferred from S II



Redfield & Falcon (2008), arXiv 0804.1802

More Results



Fundamental Issues

Locations — Geometrical arrangement in the sky, distances → distributions in 3D space

Bulk velocities — Collisions between clouds, leading to interaction zones and ρv^2 dynamical pressures?

Non-thermal velocity dispersions — Turbulence, MHD processes

Temperatures — Thermal equilibrium (& its time scale)

Densities

Next talk by Slavin will cover this topic

Compositions — Apportionment of elements in gas phase vs. dust

Ionization fractions — Density of ionizing radiation, history of the gas (ionization/recombination time scale)

Ionization Equilibrium or Lack Thereof

- Recombination time scale:

$$\frac{n_e}{dn_e / dt} = \frac{1}{\alpha n_e} = 0.7 \text{ Myr}$$

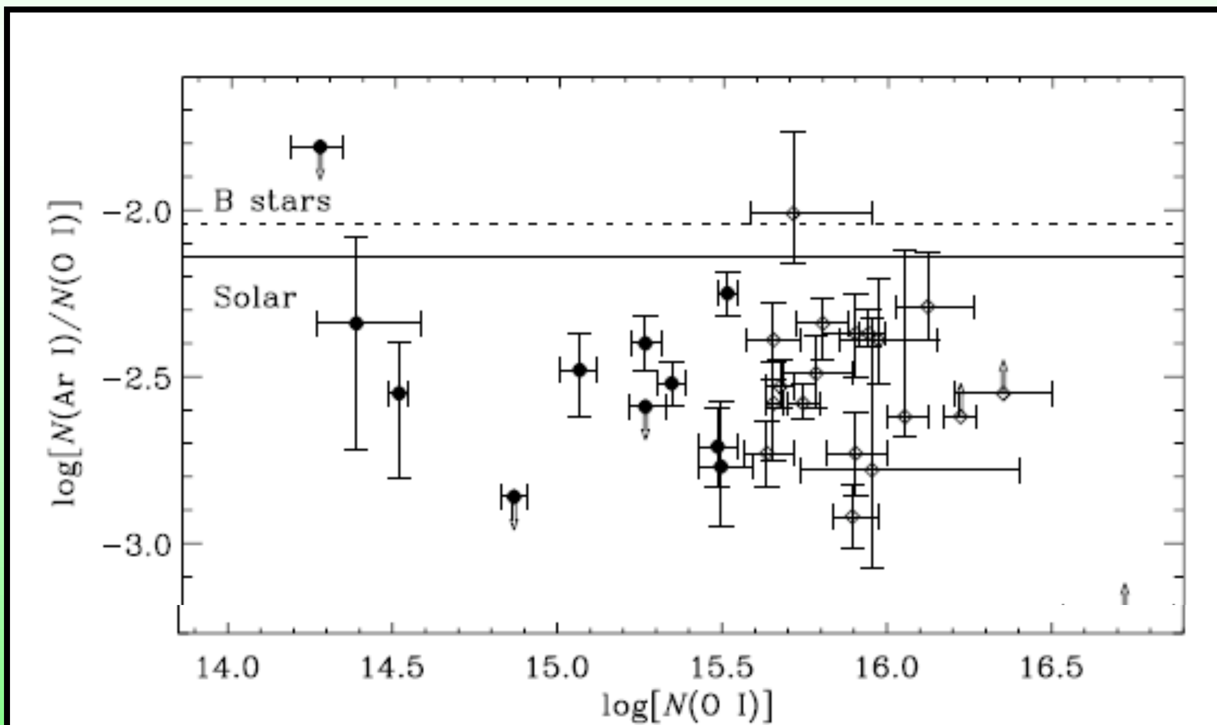
For a representative value of n_e = 0.13 cm^{-3} found by Redfield & Falcon (2008)

Argument Against the Proposal that the Local Material is Out of Equilibrium and Still Recombining

- Argon is a useful substance for testing this:
  - Should not deplete onto dust grains
  - The recombination rate for ionized Ar is about the same as that of H
  - The photoionization cross section of Ar is substantially higher than that of H (by about a factor of 10)
- If Ar/H is at about the cosmic abundance ratio, then a time-dependent recombination picture is appropriate.

Argument Against the Proposal that the Local Material is Out of Equilibrium and Still Recombining

- Results from a survey using FUSE to measure Ar and O (O is a good surrogate for H):



Lehner et al. (2003), ApJ, 595, 858